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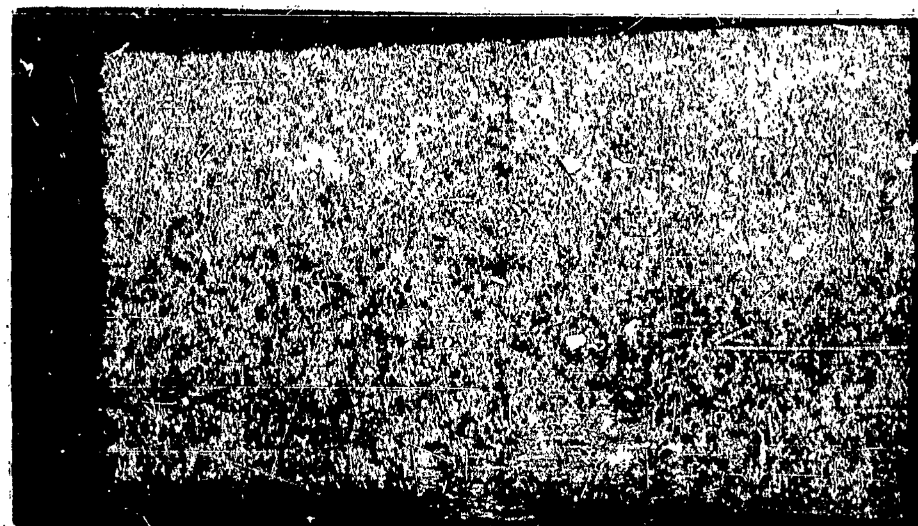

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PRINCETON UNIVERSITY

DEPARTMENT OF AERONAUTICAL ENGINEERING

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Pr.U. Aero. Engg. Rpt. No. 216d

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COMBUSTION INSTABILITY

IN

LIQUID PROPELLANT ROCKET MOTORS

Fourth Quarterly Progress Report

For the Period 1 February 1953 to 30 April 1953

Aeronautical Engineering Report No. 216d

(NOTE: This report is the FINAL Report under Contract NOas 52-713-c. Project work will be reported on a continuing basis under Contract NOas 53-817-c.)

Prepared by: Jerry Grey
J. Grey, Research Engineer

Approved by: Jerry Grey for
L. Crocco, Professor in Charge

1 June 1953

PRINCETON UNIVERSITY
Department of Aeronautical Engineering

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SE[redacted]ION

LIST OF FIGURES

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I SUMMARY

Consistent operation of the monopropellant rocket motor has been achieved at chamber pressures of from 300 to 900 psi, with artificial modulation of the propellant flow rate at frequencies up to 100 cycles per second. Thermal decomposition of ethylene oxide has not been attained, however, and in order to avoid a lengthy monopropellant rocket motor development program, it was decided to run all tests with a small amount of gaseous oxygen (F/O ratio of about 20:1). Satisfactory instrumentation performance has been achieved, although difficulties with some of the components still exist, and accuracies have not yet been precisely determined. Preliminary pressure-lag data have been taken, but it is felt that no conclusions can be drawn until more information is obtained concerning instrumentation accuracy.

Tests have been performed on the hot-wire liquid flow phasemeter to determine its frequency response. These tests show a time constant of 0.15 milli-seconds, indicating satisfactory operation at frequencies up to at least 2,000 cycles per second.

Minor modifications to the differential water-cooled catenary diaphragm pressure transducer have been made, and the instrument has been used satisfactorily on the monopropellant rocket motor. An additional modification to the water cooling passages is now being checked for resistance to high temperatures and high heat transfer rates on a "screaming" bipropellant rocket motor at the NACA Lewis Flight Propulsion Laboratory.

Design of the bipropellant rocket system has been initiated. Liquid oxygen-100% ethyl alcohol was selected as the first propellant combination

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to be tested, primarily because of the large amount of previous data on instability and performance with this combination. Construction is expected to begin early this summer, and shakedown operation of the bi-propellant system is scheduled for October.

II INTRODUCTION

A. Object

BuAer Contract NOas 52-713-c has been undertaken as a part of the jet propulsion research program of the Department of Aeronautical Engineering at Princeton to "conduct an investigation of the general problem of combustion instability in liquid propellant rocket engines. This program shall consist of theoretical analyses and experimental verification of theory. The ultimate objective shall be the collection of sufficient data that shall permit the rocket engine designer to produce power plants which are relatively free of the phenorena of instability. Interest shall center in that form of unstable operation which is characterised by high frequency vibrations and is commonly known as 'screaming'".

B. History

Interest at Princeton in the problem of combustion instability in liquid propellant rocket motors was given impetus by a Bureau of Aeronautics symposium held at the Naval Research Laboratory on the 7th and 8th of December 1950. This interest resulted in theoretical analyses by Professors M. Summerfield and L. Crocco of this Center.

Professor Summerfield's work, "Theory of Unstable Combustion in Liquid Propellant Rocket Systems" (JARS, Sept. 1951), considers the effects of both inertia in the liquid propellant feed lines and combustion chamber capacitance with a constant combustion time lag, and applied to the case of low (up to about 200 cycles per second) fre-

II INTRODUCTION (Cont'd.)

B. History (Cont'd.)

quency oscillations sometimes called "chugging".

Professor Crocco advanced the concept of the pressure dependence of the time lag in mid-1951; his paper, "Aspects of Combustion Stability in Liquid Propellant Rocket Motors" (JARS, Nov. 1951 and Jan.-Feb. 1952), presents the fundamentals resulting from this concept, and analyses the cases of low frequency instability with monopropellants, low frequency instability with bipropellants and high frequency instability, with combustion concentrated at the end of the combustion chamber.

Desiring to submit the concept of a pressure dependent time lag to experimental test a preliminary proposal was made by the University to the Bureau of Aeronautics in the summer of 1951 and, following a formal request, a revised proposal was submitted which resulted in the present contract dated 30 April 1952.

Analytical studies of distributed combustion had been carried on in the meantime under Professor Crocco's direction and within the sponsorship of the Guggenheim Jet Propulsion Center by S.I. Cheng and were issued as his Ph.D. thesis, "Intrinsic High Frequency Combustion Instability in a Liquid Propellant Rocket Motor", dated April 1952.

Time was devoted, in anticipation of the contract, during the first third of 1952 to constructing facilities, securing personnel, and planning the experimental approach.

II INTRODUCTION (Cont'd.)

B. History (Cont'd.)

During the first three month period of the contract year, personnel and facilities at the new James Forrestal Research Center were assigned, and the initial phases of the experimental program were planned in some detail.

A constant rate monopropellant feed system was designed and preliminary designs of the ethylene oxide rocket motor and the instrumentation systems were worked out. Special features of the projected systems included a pulsing unit to cause oscillations in propellant flow rate, a water-cooled strain-gage pressure pickup designed for flush mounting in the rocket chamber, and several possible methods for dynamic measurement of an oscillating propellant flow rate.

Searches were made of the literature for sources of information on combustion instability and ethylene oxide, and visits to a number of activities working on liquid propellant rocket combustion instability problems were made for purposes of familiarization with equipment and results.

The basic precepts of Crocco's theory for combustion instability were reviewed, and detailed analyses made for specific patterns of combustion distribution.

Operational tests and calibration of the Princeton-MIT pressure pickup proved the value of the design, although failure of the pickup under "screaming" rocket conditions showed the necessity for modification

II INFORMATION (Cont'd.)

B. History (Cont'd.)

of the cooling system.

Construction of the monopropellant test stand and rocket motor was completed. Modifications were made to the Princeton-MIT pressure pickup to provide for higher permissible heat-transfer rates in order that it be satisfactory for use under "screaming" conditions in a bipropellant rocket motor. Construction and preliminary testing of the hot-wire flow phase-meter and its associated equipment were completed.

Subsequent efforts are presented in detail in this report.

C. Schedule

1. Operations

It has been decided that since theoretical analysis of the high-frequency instability bipropellant case has progressed so satisfactorily, detailed experimental studies of monopropellant rockets and of low-frequency instability in bipropellant rockets have been deemed unnecessary, and have been dropped from the program. This decision involved a certain amount of rescheduling, as indicated by Figure 1.

2. Reports

A new contract, NOas 53-817-c, has been granted by the Bureau of Aeronautics as of 1 March 1953 to continue the work originally authorized under the subject contract, NOas 52-713-c. Since the new contract is a direct con-

II INFORMATION (Cont'd.)

C. Schedule (Cont'd.)

2. Reports (Cont'd.)

tinuation of the present effort, this Fourth Quarterly Progress Report will replace the Final Report originally specified by NOas 52-713-c. Also, since the new contract overlaps the present one by two months, the Fifth Quarterly Progress Report (i.e., the first quarterly of Contract NOas 53-817-c) will cover the period from 1 May to 31 July 1953.

III APPARATUS

A. Monopropellant Rocket Motor

Several different motor configurations were used in an effort to obtain decomposition of ethylene oxide, as will be described later in this report. The final arrangement, which has been used on all subsequent tests to date, is illustrated in Figure 2. This configuration features three cylindrical sections each 6" long, used with the original nozzle, providing an L^* of about 820 inches. Ignition is supplied by two Bendix-Scintilla high-pressure high-power spark plugs energised by a Bendix-Scintilla TIN-10 generator unit. The ethylene oxide injection pattern is unchanged from the configuration illustrated in the Third Quarterly Progress Report, as is the location of the gaseous oxygen inlet port. The oxygen port (in the head end of the motor) has been fitted with an orifice to provide measurement of oxygen flow rate.

The pulsing unit was delivered in March. Although it has been used on several runs, to be discussed later in this report, several modifications will be required before it is completely satisfactory for application to time-lag measurements. The drive motor was underpowered, and a larger drive has been ordered. The original motor is now in current use, but has the disadvantage of slowing up during a run so that a constant flow modulating frequency cannot be obtained. The graphitar piston sealing ring proved entirely unsatisfactory, and has been replaced with a double teflon "O"-ring which, however, must be replaced every three or four runs. The main connecting rod bearing has shown appreciable wear, and, although this condition was somewhat relieved by the addition of a pressurised lubricant

III APPARATUS (Cont'd.)

A. Monopropellant Rocket Motor (Cont'd.)

supply, the oilite sleeve will shortly be replaced by a needle bearing. Despite these difficulties, the unit has been in continuous use at frequencies up to 150 cycles per second (9,000 RPM). Photographs of the unit as installed on the thrust stand appear in Figures 3 and 4.

The monopropellant tank has finally replaced the interim tank illustrated in the Third Quarterly Progress Report. The new tank installation, shown in Figure 5, features a full length high-pressure sight glass which may be used to make accurate measurements of average propellant flow rates.

B. Instrumentation

All instrumentation required for the monopropellant system has been delivered, with the exception of the four-channel filter. Some of the items, however, are inactive or had to be returned due to malfunction or failure to meet specifications. The Ampex magnetic tape recorder head was returned to the vendor for adjustments to the high-speed playback circuit, the Li mass flowmeter was again returned to have its excessive leakage corrected, and a sufficient number of circuit difficulties have been encountered on the Mittelmann electromagnetic flowmeter to preclude even a steady-state calibration of the instrument. The major problem encountered, however, has been the matching of the Advance Electronics DC differential amplifier to other circuit components. A solution to this problem has been evolved which requires a difference in ground level of 112 volts between input and output signals of the amplifier, and, although

III APPARATUS (Cont'd.)

B. Instrumentation (Cont'd.)

the instrument has been operated satisfactorily under these conditions, convenience dictates that an alternate amplifier be obtained. Fortunately, it is expected that only a slight delay in the overall schedule will be occasioned by this development.

In order to take full advantage of the dual channel oscilloscope, a General Radio strip film oscillograph camera with a film speed range of from 5 inches to 35 feet per second has been obtained. Operation of this instrument combination has proven satisfactory, as is evidenced by the hot-wire data included later in this report. As soon as the tape recorder head is returned, a series of calibrations will be made on all recording instruments to determine their relative accuracy and reproducibility.

Operation of the Princeton-MIT water-cooled double catenary diaphragm pressure pickup has been satisfactory in the monopropellant system. Further calibrations have been postponed due to the urgency of obtaining sufficient rocket motor operational data to check out the system, but these calibrations will be made during the next report period. Individual balancing bridges and power supplies have been constructed for each projected channel, and have been inserted in the rocket motor control panel as shown in Figure 6. This equipment has operated satisfactorily on all runs to date.

The differential pickups now on hand are all of the original coolant passage design, which was demonstrated to be inadequate for flush-mounting

III APPARATUS (Cont'd.)

B. Instrumentation (Cont'd.)

in a screaming bipropellant rocket. (See the Second Quarterly Progress Report). Two "dummy" pickups (i.e., without strain-sensing element) featuring a coolant passage modification which will increase the allowable heat transfer have been delivered to the Rocket Laboratory at the NACA Lewis Flight Propulsion Laboratory in Cleveland for operation under bipropellant screaming conditions, and results will be reported as soon as they become available. An entirely different strain-gage pickup designed by the Control Engineering Corporation of Norwood, Massachusetts has also been delivered to the NACA for evaluation. The basic design of this pickup follows the original Li-Draper patent in that it incorporates a single catenary diaphragm which actuates a cylindrical strain tube, but cooling is accomplished by spraying water directly onto the back of the diaphragm.

Several minor modifications have been made to the differential pickup which have been successful in eliminating back pressure leakage and breakage of the necessarily small back pressure fitting. No difficulties of any sort have yet been encountered in operation of the absolute pressure pickup. Figure 7 shows one operating configuration in which a differential pickup is mounted in the chamber and an absolute pickup in the injector of the monopropellant rocket motor.

The hot-wire flow phasemeter has been calibrated for frequency responses in several different ways, as described later in this report, and is now ready for installation in the flow calibration rig. The flow rig

III APPARATUS (Cont'd.)

B. Instrumentatian (Cont'd.)

has been set up as shown in Figure 8 (minus an instantaneous flowmeter due to forementioned difficulties with the Mittelmann and Li meters) and nonsteady-state calibration of the monopropellant injector orifices will be initiated in the near future.

C. Bipropellant Rocket Motor and Feed System

The first propellant combination to be evaluated in the bipropellant studies was selected to be liquid oxygen and ethyl alcohol, primarily because of the large amount of data previously accumulated on the performance and instability characteristics of this combination. The flow system, thrust stand, rocket motor, and instrumentation system have been laid out, and after finalisation of design details, purchasing of components and construction of the test stand will begin.

The flow system as presently conceived consists of pressurised stainless steel tanks feeding through Potter flowmeters, cavitating venturis, and a pulsing, or rather flow modulating unit, the latter consisting of two pistons whose phase can be adjusted with respect to each other. This configuration will be used only until the significance of the combustion time lag in bipropellant motors is established, and the flow modulating unit will be removed before studies of actual instability are begun.

The rocket motor will consist of an uncooled copper chamber, in which the chamber pressure pickups will be mounted, with a water-cooled

III APPARATUS (Cont'd.)

C. Bipropellant Rocket Motor and Feed System (Cont'd.)

copper nozzle and an impinging-stream injector patterned after a design used extensively by Reaction Motors, Incorporated for instability and performance studies. Chamber pressures ranging from 300 to 900 psi will be used, resulting in a thrust range of approximately 250 to 800 pounds.

The instrumentation system will be patterned after the present monopropellant system, utilizing the double-diaphragm water-cooled pressure pickups as its principal feature. Additional high-frequency, high performance instruments such as another multi-beam oscilloscope and multichannel FM tape recorder (or adaptation of the present recorder) will also be required.

Details of the final system designs will be presented in the Fifth Quarterly Progress Report of Contract NOas 53-817-c.

IV INFORMATION AND DATA

A. Monopropellant Rocket Motor

Testing during this report period consisted of three parts: shakedown operation of the monopropellant motor, steady-state tests to determine operating limits of oxygen flow, and nonsteady tests (during which the ethylene oxide flow rate was modulated by the pulsing unit), the primary purpose of the latter being checkout of the instrumentation. Summaries of the three phases are as follows:

1. Shakedown operation

The first series of tests was made with the rocket motor configuration illustrated in Figure 3 of the Third Quarterly Progress Report, consisting of two cylindrical sections each six inches long and five inches inside diameter, and the same nozzle and head-plate shown in Figure 2 of the present report. L^* for this motor was 570 inches. Operation of the motor was satisfactory as long as gaseous oxygen flow was maintained, but decomposition of ethylene oxide could not be sustained when the oxygen was cut off. A number of configuration changes were tried at chamber pressures from 300 to 700 psi without success (see Monthly Progress Report for March, 1953 for details), culminating in two runs which resulted in failure of the necked-down nozzle flange bolts. No significant damage to motor or thrust stand components occurred (see Figure 9), and the explosions were later traced to insufficient spark ignition. This was corrected both by using two plugs firing alternately instead of the single plug utilized at the time the failures occurred, and increasing the voltage supply to the ignition generator unit. No subsequent failures have occurred since these measures were taken.

IV INFORMATION AND DATA (Cont'd.)

A. Monopropellant Rocket Motor (Cont'd.)

1. Shakedown operation (Cont'd.)

It was decided at this point that since development of a monopropellant motor utilising the pure decomposition of ethylene oxide would consume valuable contract time and money, and since small amounts of gaseous oxygen would not affect the application of the time-lag instability theory to monopropellant rocket motors, the technique of using oxygen would be employed on all future "monopropellant" tests. The next step, then, was to determine how much oxygen was required, and to establish an operating value of O/F ratio.

2. Operating Limits of Oxygen Flow Rate

An orifice was installed in the oxygen injection port, and calibrations were made using Fischer-Porter gas Flowrators. The accuracy of these calibrations is probably no better than ten percent, but since the only purpose of this measurement was to establish some fixed operating condition, higher degrees of accuracy were deemed unnecessary.

A series of steady-state tests of ten seconds duration were made. Keeping the ethylene oxide flow rate constant, the gaseous oxygen flow was varied from a point at which the reaction would not start to a value at which performance became nearly constant. This was repeated for three values of ethylene oxide flow rate, corresponding to nominal chamber pressures of 300, 600, and 900 psi.

The results of these tests appear in Figure 10, which plots specific impulse against oxygen-ethylene oxide ratio for the three values of

IV INFORMATION AND DATA (Cont'd.)

A. Monopropellant Rocket Motor (Cont'd.)

2. Operating Limits of Oxygen Flow Rate (Cont'd.)

ethylene oxide flow rate. Also included are several comparison runs at different values of L^* obtained by removing one section from the motor pictured in Figure 2.

Each point of Figure 10 represents one run. Ethylene oxide flow rate was obtained by a Potter flowmeter, with an estimated accuracy of $\pm$ 1%, and thrust from a Li strain-gage load cell recording on a Leeds and Northup "Speedomax" potentiometer, with an estimated overall accuracy of $\pm$ 2%.

3. Operation With Modulated Propellant Flow Rate

These tests were run with the motor configuration of Figure 2 at a nominal chamber pressure of 600 psi, using the pulsing unit shown in Figure 4. The pressure pickup configuration used was that shown in Figure 7 with one pickup in the chamber and one in the injector, and the pressure data was recorded simultaneously on magnetic tape (after having passed through Ballantyne A.C. amplifiers), and on the recording oscillograph (after amplification through Brush D.C. amplifiers). Typical D.C. recordings of one run (No. 43) are shown in Figures 11a, 12, and 13, showing the start, a point two seconds after the start, and a point 9 seconds after the start. Figure 11b illustrates, for comparison purposes only, typical D.C. data from a run without flow modulation (No. 48). Figure 14 shows an unfiltered section of Run 43 which was played back into the oscillograph from the Ampex tape recorder at one-twentieth of recording tape speed, and clearly illustrates the excellent time-scale resolution which can be obtained in this

IV INFORMATION AND DATA (Cont'd.)

A. Monopropellant Rocket Motor (Cont'd.)

3. Operation with Modulated Propellant Flow Rate (Cont'd.)

way, despite the fact that it represents only one-fourth of the maximum possible time-scale amplification which can be obtained. Note that the data of this figure was taken through an A.C. amplifier, and hence only the modulated portion of the signal appears on the figure.

A plot of modulating frequency against time for the illustrated run appears in Figure 15, clearly demonstrating the pulsing unit slowdown caused by the fact that the drive motor was underpowered. The magnitude of the pressure oscillations resulting from flow rate modulation are shown in the same figure.

B. Hot-Wire Flow Phasemeter

Tests to determine the time constant of a suitable hot-wire configuration were made as a unit investigation, the results of which are presented in Appendix A. All information and data are included in the body of the Appendix. It is intended that development of this item will be continued toward ultimate use in the calibration of pressure pickups to measure instantaneous flow as described in the Third Quarterly Progress Report.

V DISCUSSION

A. Monopropellant Rocket Motor Tests

1. Shakedown operation

A number of possible explanations have been offered for the failure of the monopropellant rocket to decompose ethylene oxide without the presence of oxygen. A few of these include (a) unsuitable injection pattern, (b) excessive mass-flow-to-volume ratio, (c) excessive number of droplets for available reaction volume*, etc. Unfortunately, however, so little is known about the physical and chemical characteristics of monopropellant decomposition that no definite cause can be quickly established. The attack would thus, of necessity, become a purely empirical test program such as has been pursued by other monopropellant rocket experimenters, and expenditure of the required time and money for such a program was not deemed advisable or necessary to the subject study; hence the decision to operate with small amounts of oxygen was made. Later tests indicated that only minute amounts of gaseous oxygen were required to sustain the reaction, and, as will be illustrated below, the percentage change in performance characteristics which results from the use of oxygen is of the order of experimental instrument error.

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* See L.A. Wiseman, "Liquid Propellants": An Analysis of the Factors Determining Combustion Efficiency and Sensitiveness", British Ministry of Supply, Explosives Research, and Development Report No. 42/R/51 - SECRET DISCREET

V DISCUSSION (Cont'd.)

A. Monopropellant Rocket Motor Tests (Cont'd.)

2. Operating Limits of Oxygen Flow Rate

Figure 10 shows that the performance of the "monopropellant" rocket increases appreciably up to some value of O/F ratio, after which the increase is more gradual. It is believed that the initial rapid rise represents the improvement in percentage of decomposition, which reaches its maximum value in the neighborhood of the "knee". The continued small increase in performance with O/F ratio after passing the "knee" results from the additional energy supplied by the oxygen-ethylene oxide combustion, which would eventually reach a peak at or near the stoichiometric mixture ratio. The desired operating point would be at an O/F ratio sufficiently high above the "knee" so that the 10% variations in ethylene oxide flow rate induced by the pulsing unit will never result in an O/F ratio below the "knee". This is necessary in order to isolate the essentially physical effects of the flow-rate oscillations from the chemical effects of change in percentage decomposition of propellant mass due to insufficient oxygen. Typical operating points are indicated in the figure.

The check points taken at lower values of L^*, although not sufficiently numerous to be conclusive evidence, indicate that performance is sensitive to this parameter, and hence the future standard motor configuration will include all three sections.

The figure also illustrates that the effect of the oxygen flow on performance when the ethylene oxide oscillates about the operating point at an amplitude of $\pm$ 10% is of the order of only $\pm$ 0.7%, and hence is

V DISCUSSION (Cont'd.)

A. Monopropellant Rocket Motor Tests (Cont'd.)

2. Operating Limits of Oxygen Flow Rate (Cont'd.)

negligible compared to the major effect of the ethylene oxide flow variations (estimated at 10% to 20%).

3. Non-steady operation

As was pointed out in the previous section, these tests were performed solely for the purposes of equipment checkout, since the performance of the instrumentation has not as yet been accurately determined. The data presented should be considered as illustrative of the character of the measurements which can be obtained, but because of the unknown accuracy of calibrations, etc., and of the shortcomings of the interim amplifiers used, application to time-lag theory can not be made with this data. It is expected that suitable data will be available for analysis in the Fifth Quarterly Progress Report. Figures 11a and 11b show typical starts of modulated and unmodulated runs respectively as recorded on the 6-channel Hathaway oscillograph after amplification by a standard D.C. Brush carrier amplifier. The low response of this instrument (of the order of 300 cps) damps out any high frequency oscillations, but the effect of the flow pulsing unit (initially set at 100 cps) is clearly shown in both the chamber pressure and injector pressure.

The uppermost trace is a reference frequency of 100 cps. The middle trace is the chamber pressure as recorded by a flush-mounted differential pickup, and the lower trace, which crosses over the middle one during the start phase, is the feed line pressure as measured by an absolute pressure

V DISCUSSION (Cont'd.)

A. Monopropellant Rocket Motor Tests (Cont'd.)

3. Non-steady operation

pickup mounted in the injector (see Figure 7). The effect of slowdown of the pulsing unit is clearly illustrated by Figures 12 and 13, which show later portions of the same run. Figure 12 is taken at a point two seconds after start and Figure 13 at nine seconds after start. The decreases in both frequency and feed-line oscillation amplitude are obvious, and are more clearly shown in the curves of Figure 15. The decrease in feed-line pressure amplitude results from the fact that the flow rate oscillation is achieved by varying the feed-line volume, so that the flow rate, and hence the pressure, are dependent not on the displacement of the modulating piston, but on the rate of change of that displacement. Hence, as the frequency of oscillation decreases, the rate of change of displacement decreases, showing up in the data as a decrease in feed-line pressure amplitude.

The capabilities of the instrumentation system in the reproduction of data may be observed in Figure 14. The data of this figure are from the same run as those of Figures 11, 12, and 13, but were recorded in a different manner. The outputs from the pickups were passed through A.C. amplifiers, recorded on magnetic tape running at 60 inches per second, and played back at 3 inches per second into the Hathaway oscillograph. (Note that the oscillograph chart speed was set at 50 inches per second, only one-quarter of its maximum speed of 200 inches per second). Again, the uppermost trace is the 100 cps reference, the middle is the chamber pressure pickup output, and the lower is the feed-line pressure as recorded by a pickup mounted in the injector. Here, not only the 100 cps (approximately) modulating fre-

V DISCUSSION (Cont'd.)

A. Monopropellant Rocket Motor Tests (Cont'd.)

3. Non-steady operation

quency appears, but the injector trace also shows clearly a 3900 cps oscillation which is apparently a characteristic of the feed line. Again, this particular bit of data can not be used directly for time-lag studies due to the phase-shift characteristics of the interim amplifiers and to calibration inaccuracies, but the figure clearly demonstrates the ability of the recording system to resolve high-frequency signals into records whose clarity will permit highly accurate analysis.

B. Hot-wire Liquid Flow Phasemeter

Discussion of the results of testing of this instrument appears in Appendix A, which is a unit report of all work accomplished to date on the hot wire.

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FIGURE 1

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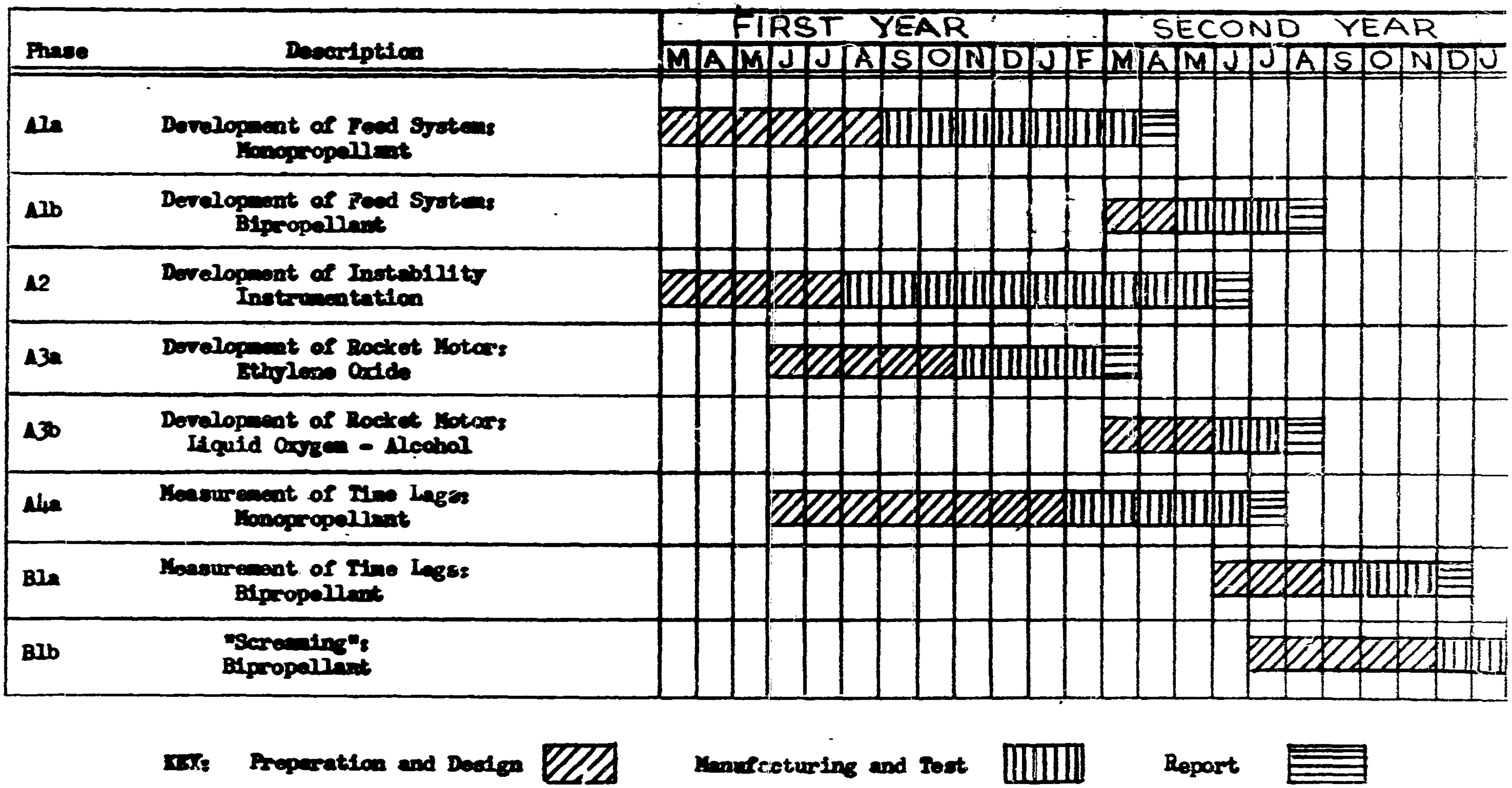

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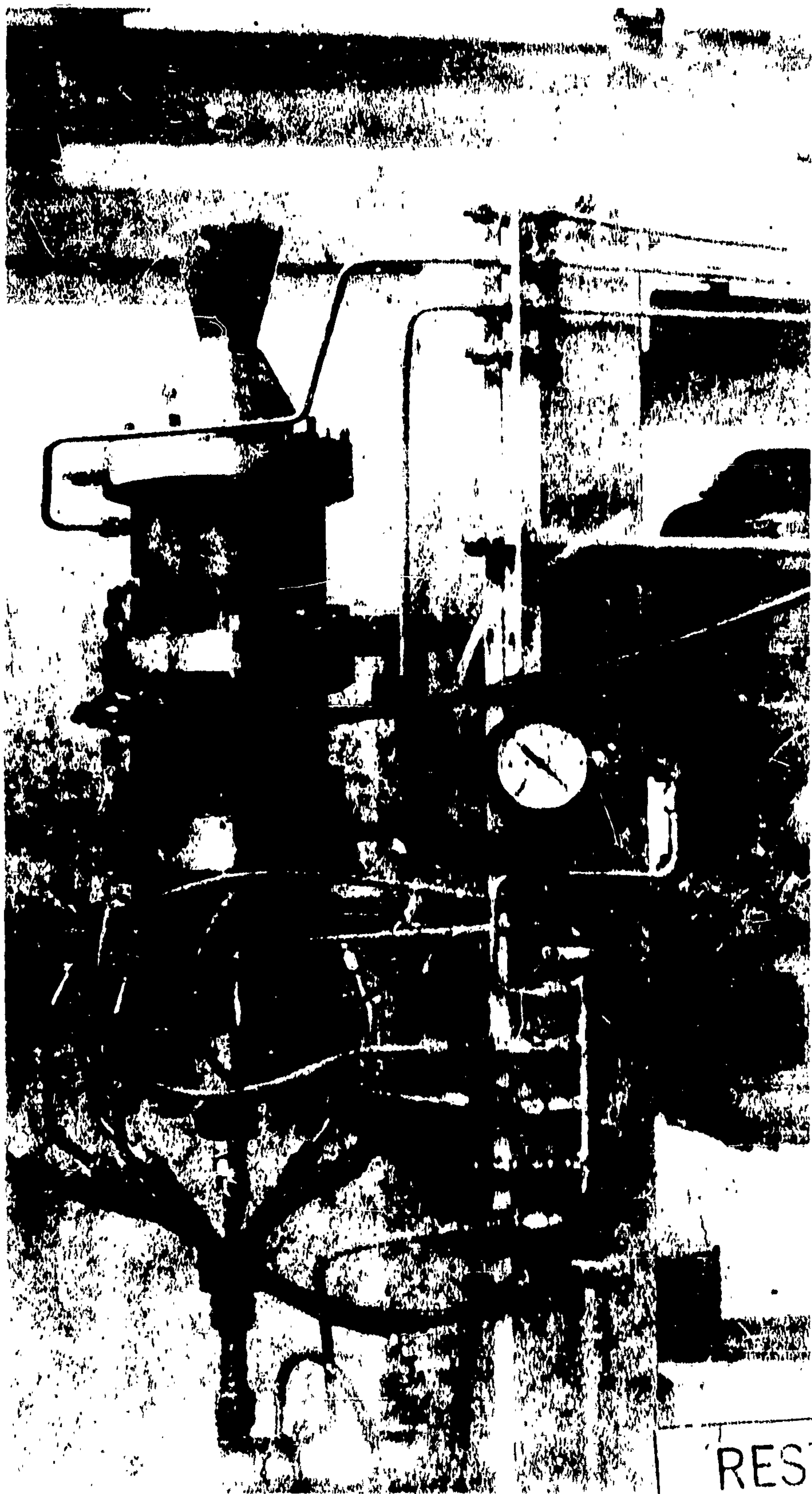

FIGURE 2
PRESENT CONFIGURATION OF
MONOPROPELLANT ROCKET MOTOR

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FIGURE 3: MONOPROPELLANT PULSING UNIT AND 3/4 H.P. DRIVE

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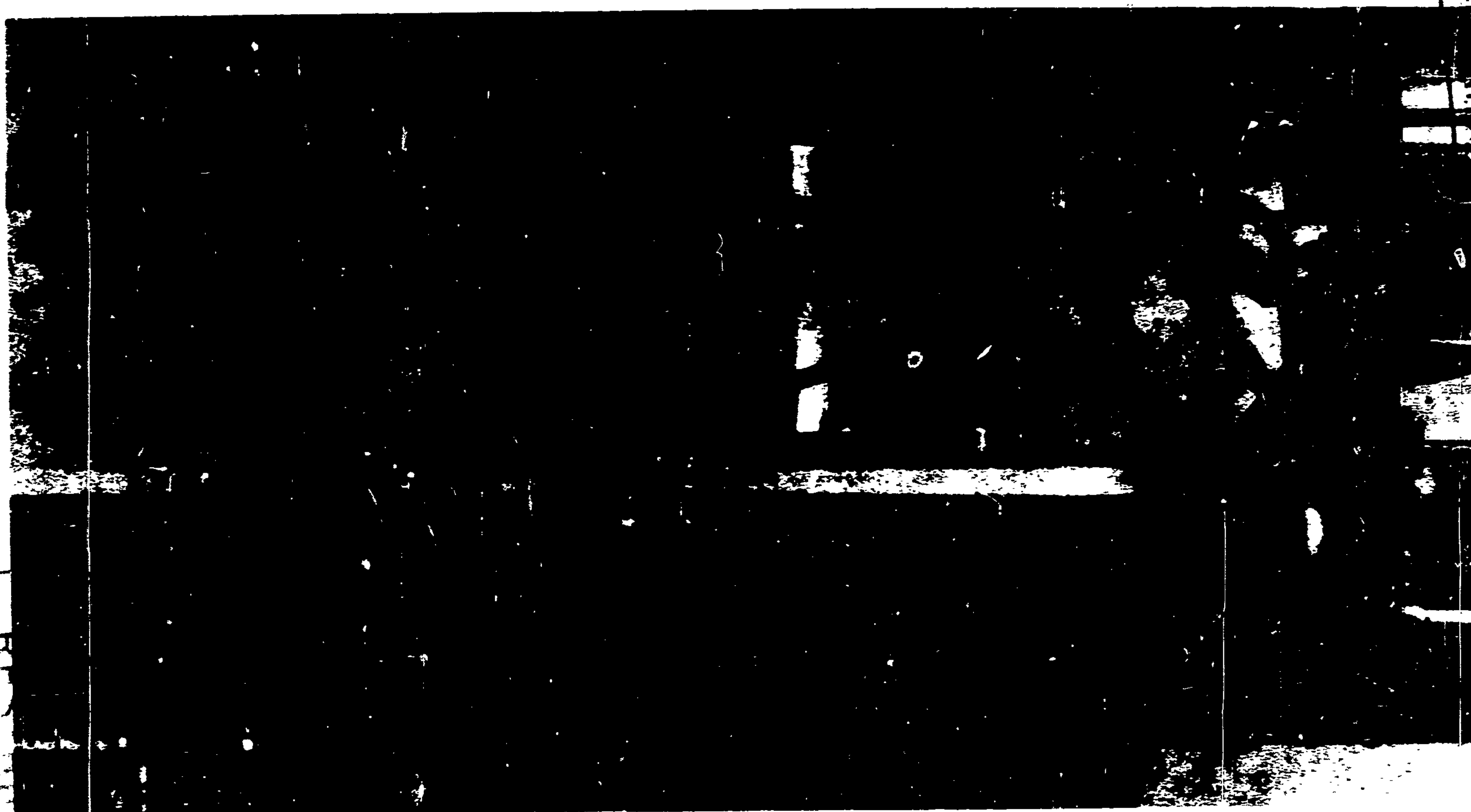

FIGURE 4:
MONOPROPELLANT PULSING UNIT

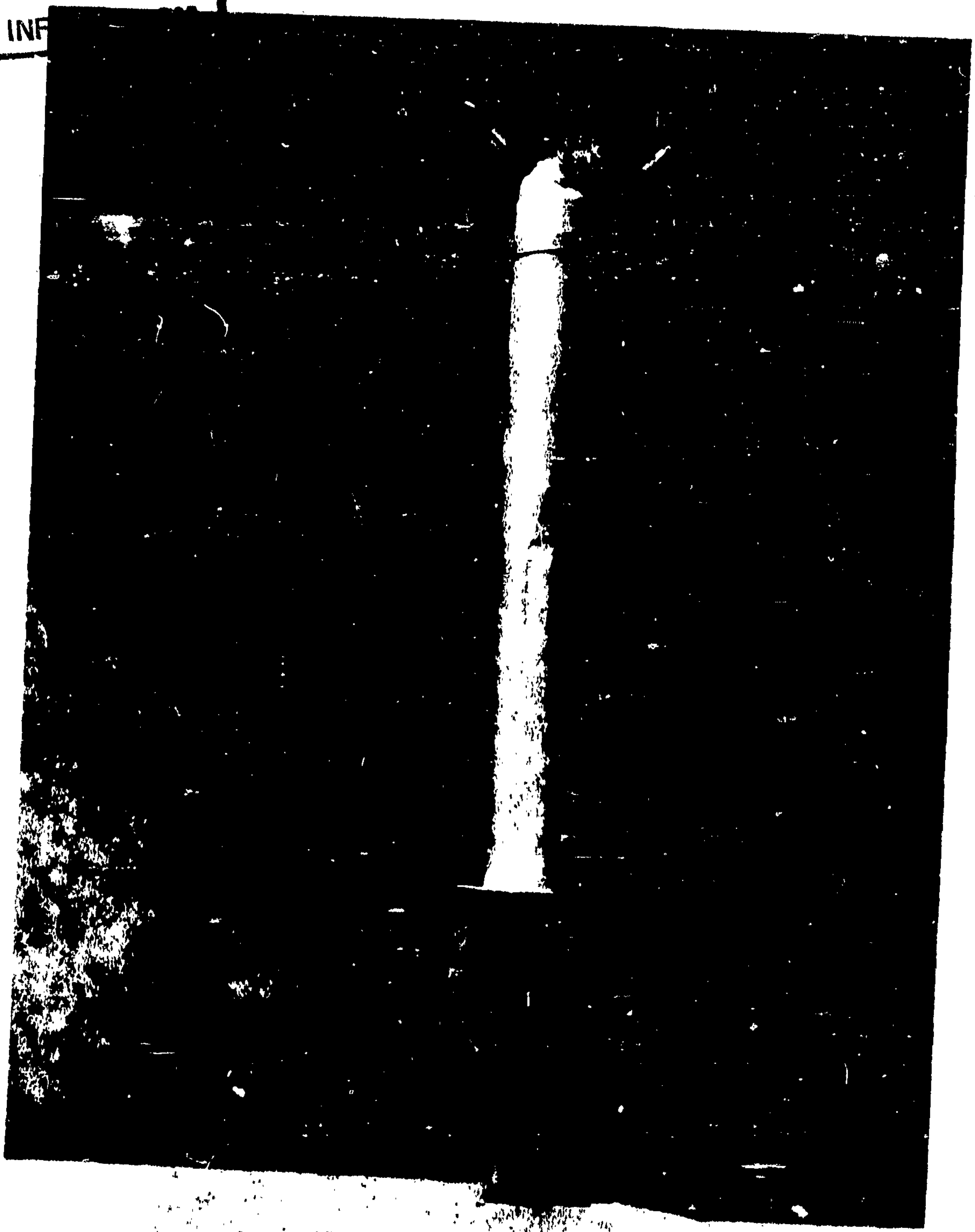

FIGURE 5:
HIGH PRESSURE MONOPROPELLANT
TANK INSTALLATION

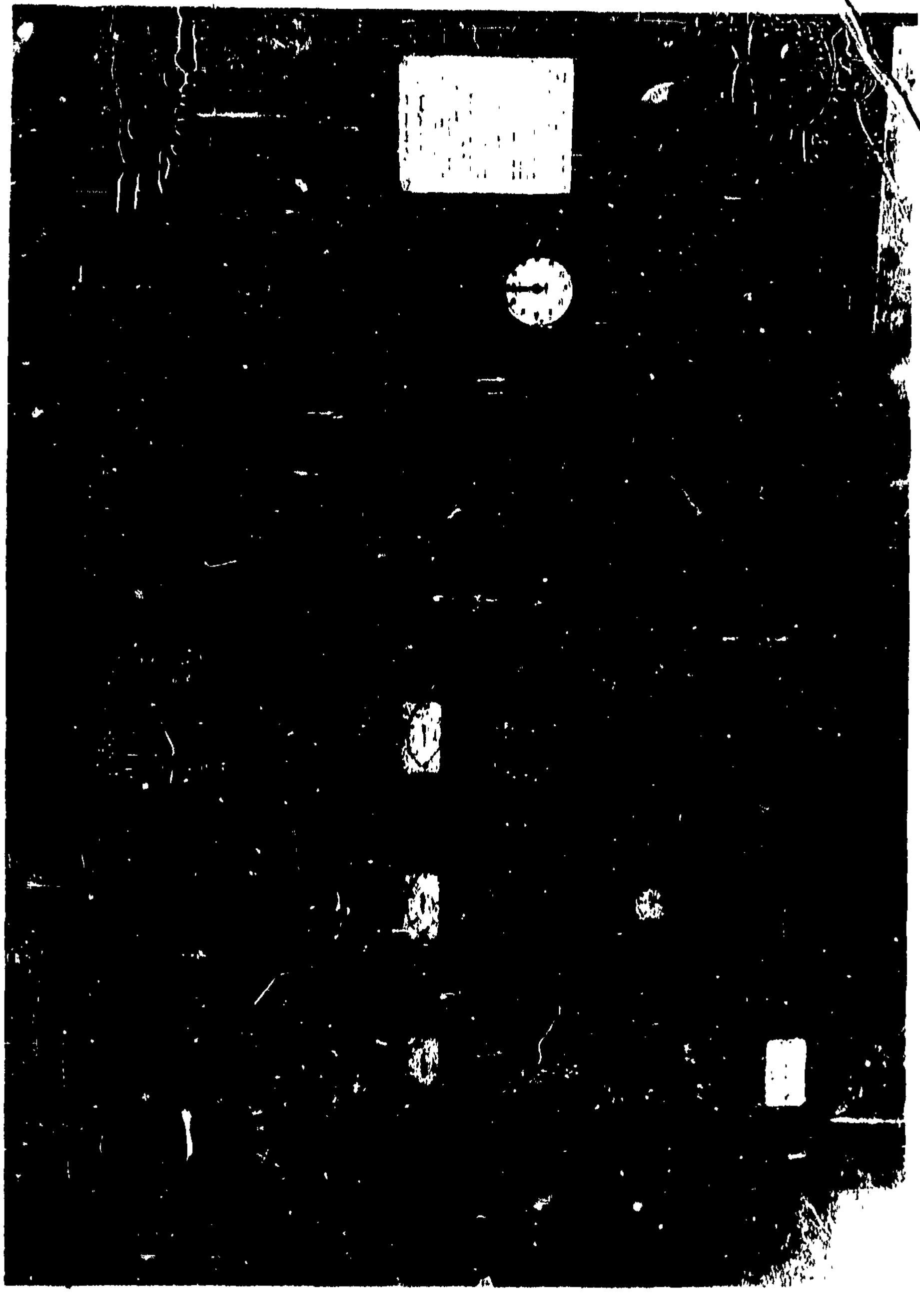

FIGURE 6:
INSTALLATION OF PRESSURE PICK-UP
BALANCING BRIDGES AND POWER SUPPLIES

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FIGURE 7:
INSTALLATION OF PRESSURE PICKUPS
IN THE MONOPROPELLANT ROCKET MOTOR

FIGURE 8:
EXPERIMENTAL SETUP FOR DETERMINATION OF
INSTANTANEOUS FLOW-PRESSURE RELATIONSHIP

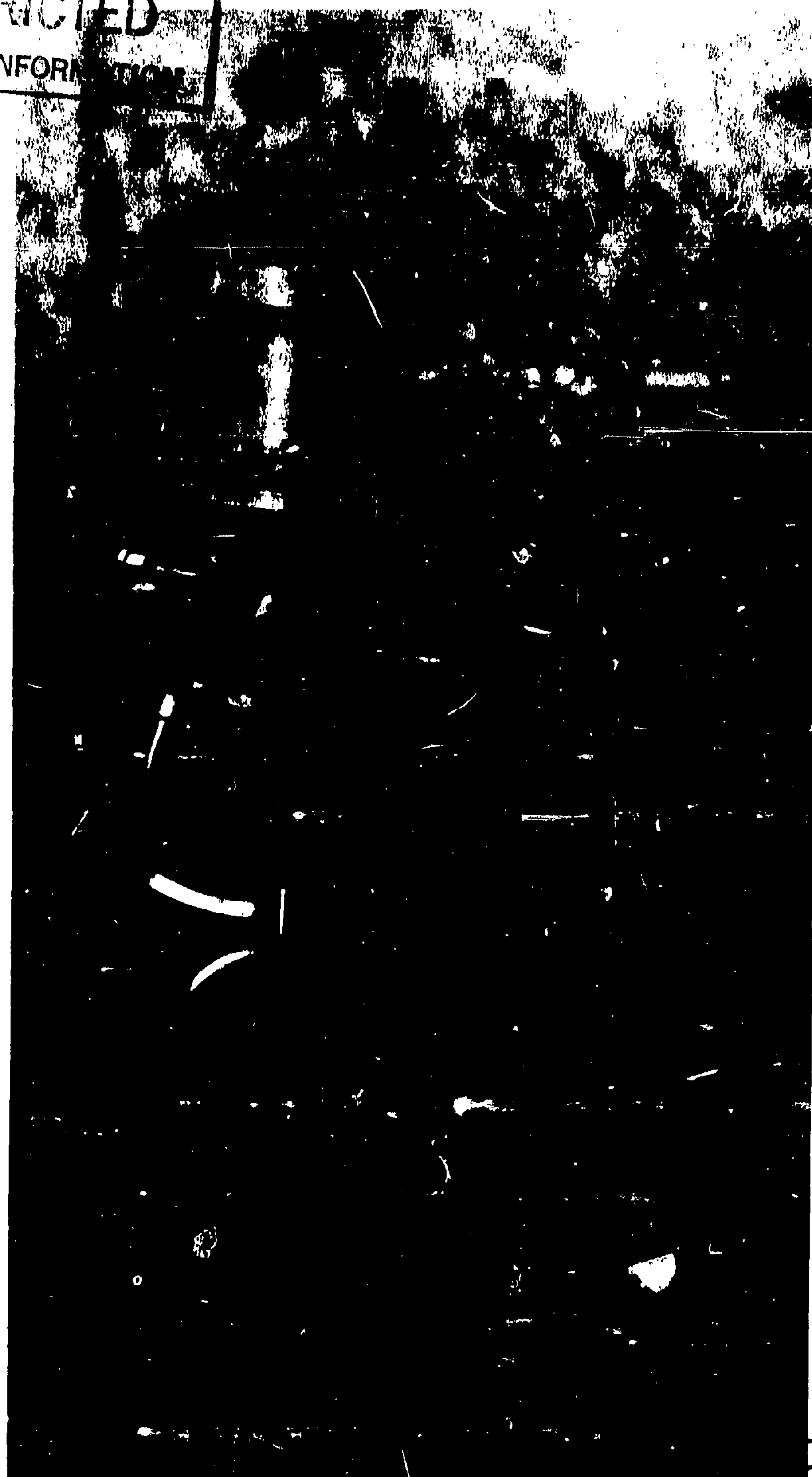

FIGURE 9:
MONOPROPELLANT ROCKET MOTOR AFTER FAILURE OF NECKED DOWN NOZZLE FLANGE BOLTS ON RUN NO. 13

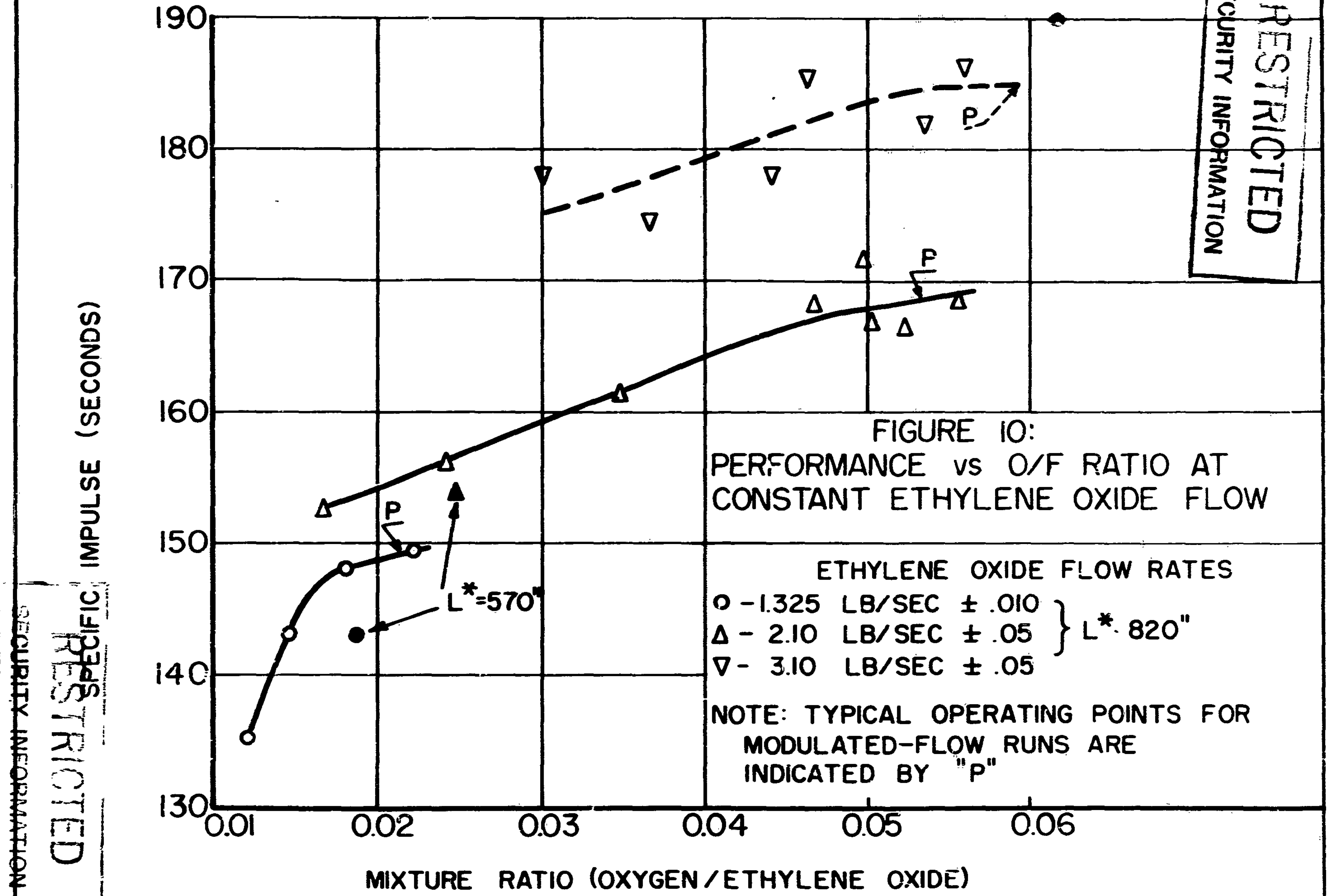

FIGURE 10:
PERFORMANCE vs O/F RATIO AT CONSTANT ETHYLENE OXIDE FLOW

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FIGURE 11a
DC RECORDING OF START OF MODULATED RUN

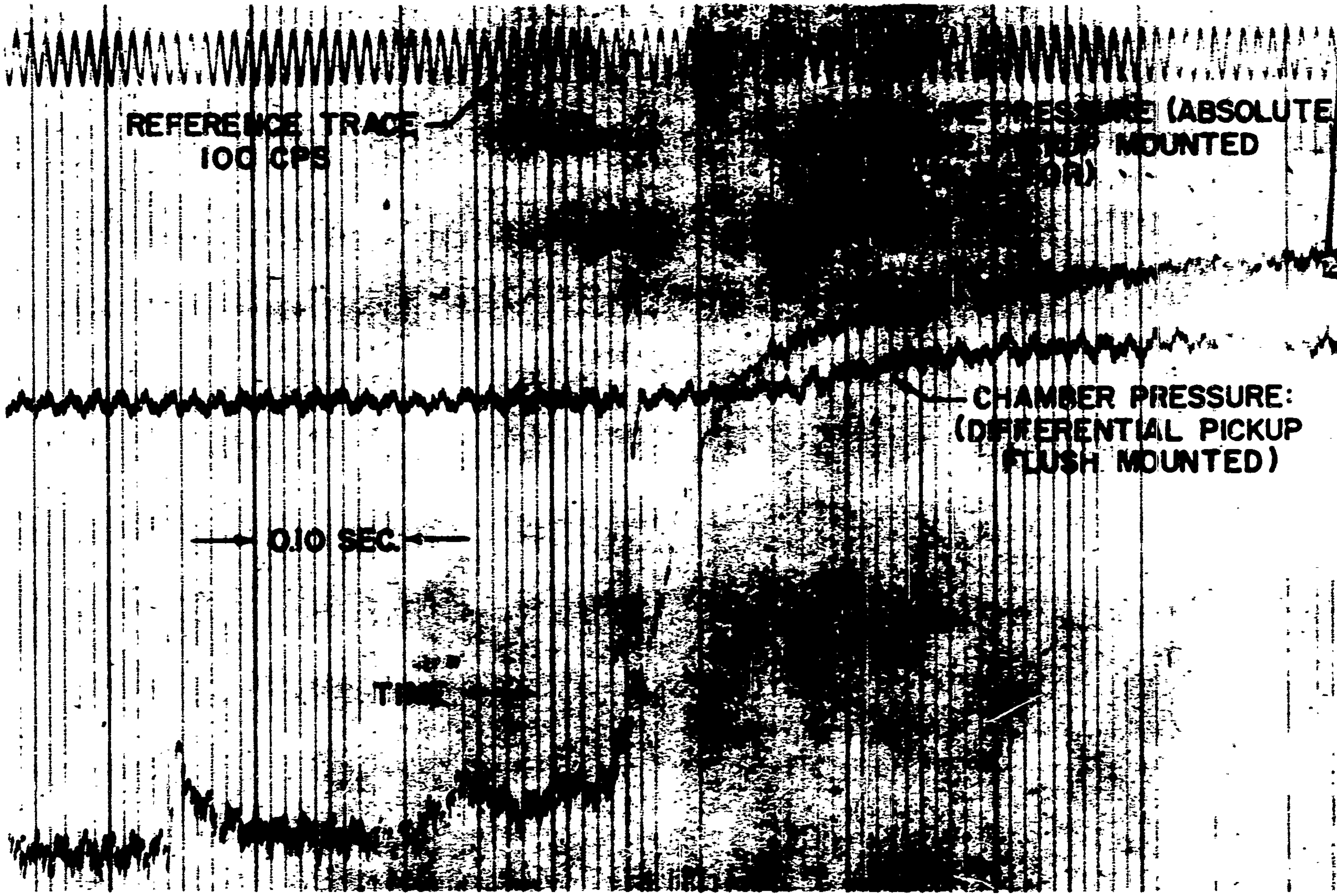

FIGURE 11b
DC RECORDING OF START OF UNMODULATED RUN

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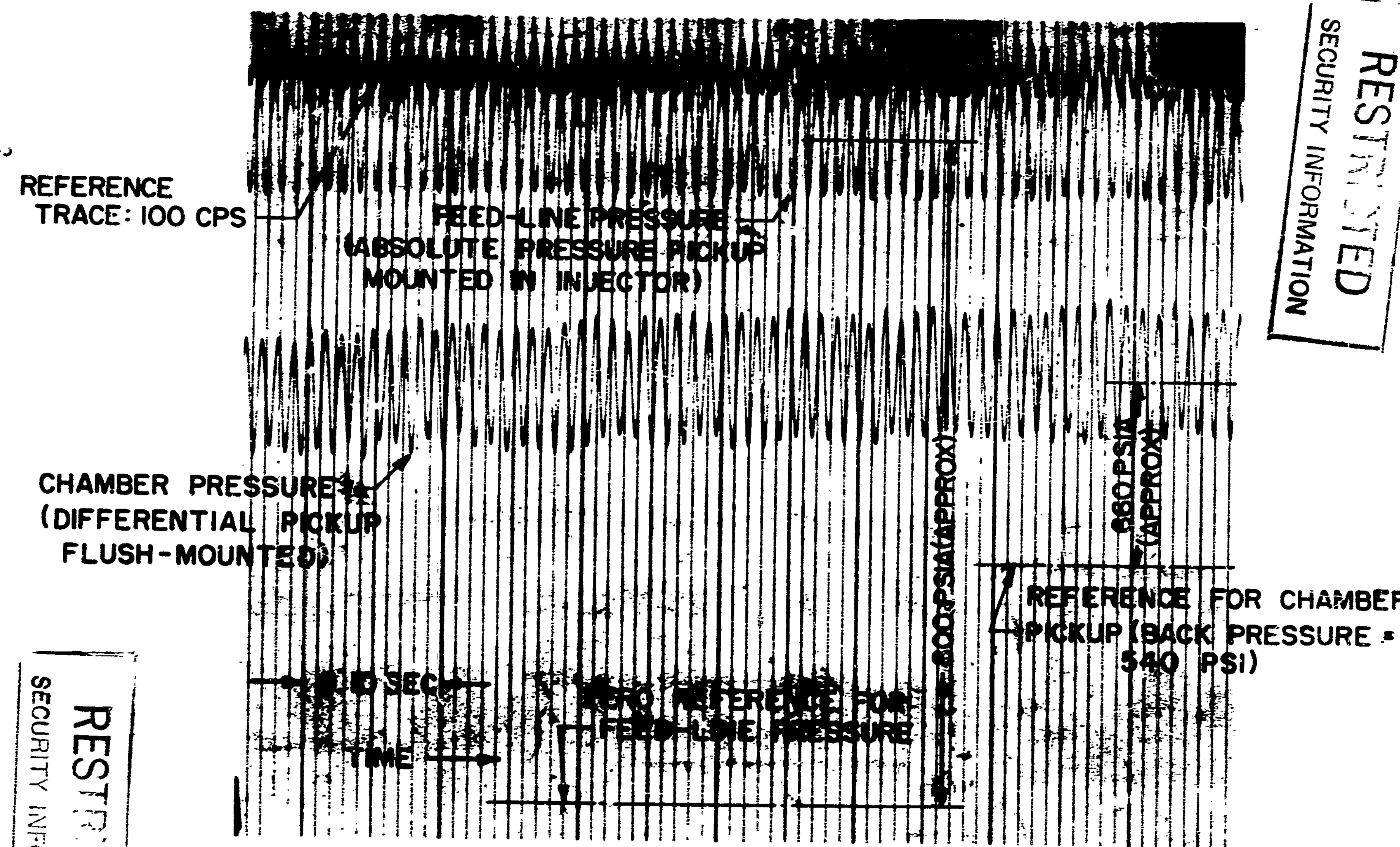

FIGURE 12:
DC RECORDING OF MODULATED RUN: 2 SECONDS AFTER START

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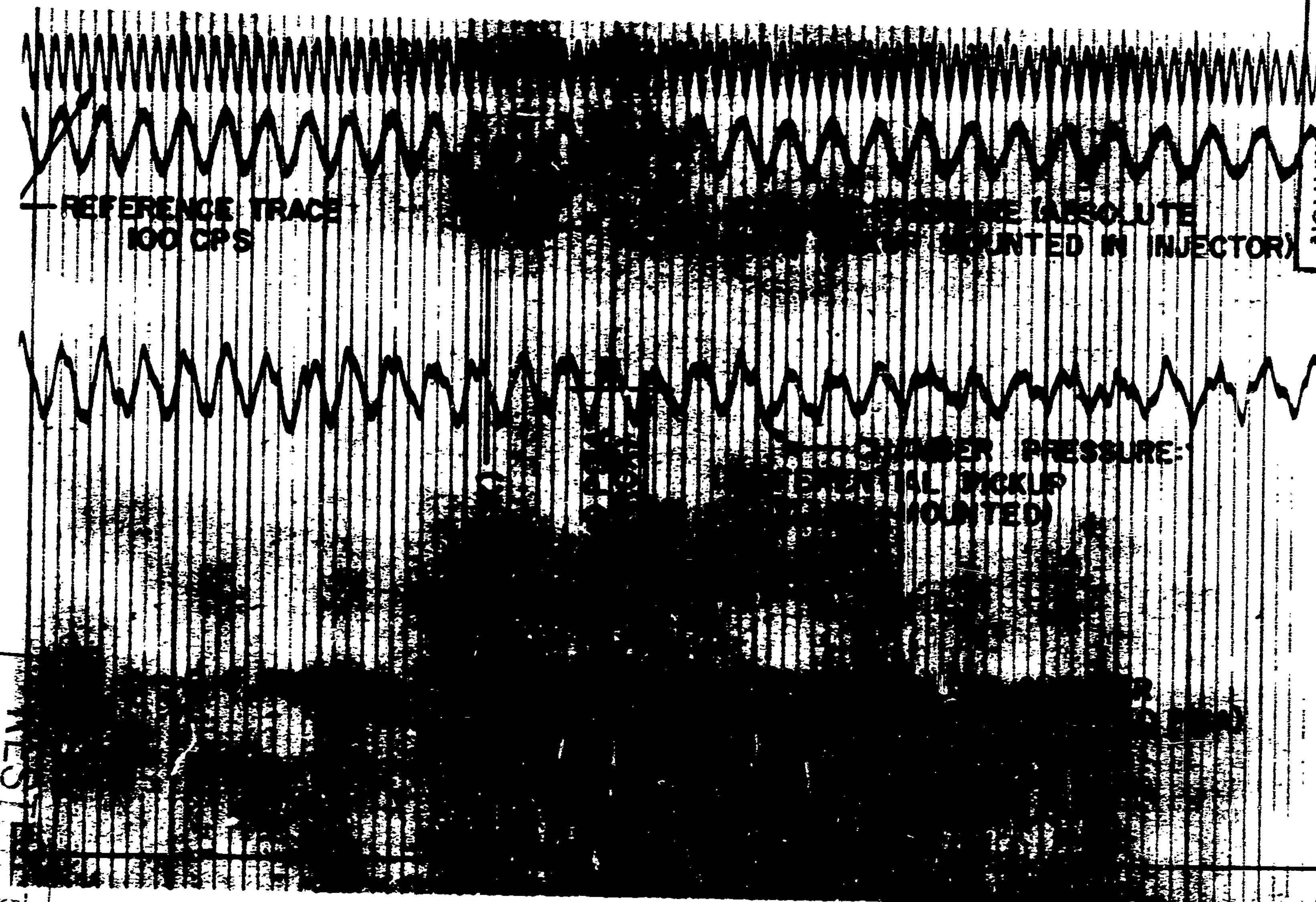

RESTRICTED
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FIGURE 13:
DC RECORDING OF MODULATED RUN: 9 SECONDS AFTER START

FIGURE 14:
AC PLAYBACK RECORDING OF MODULATED RUN

RESTRICTED
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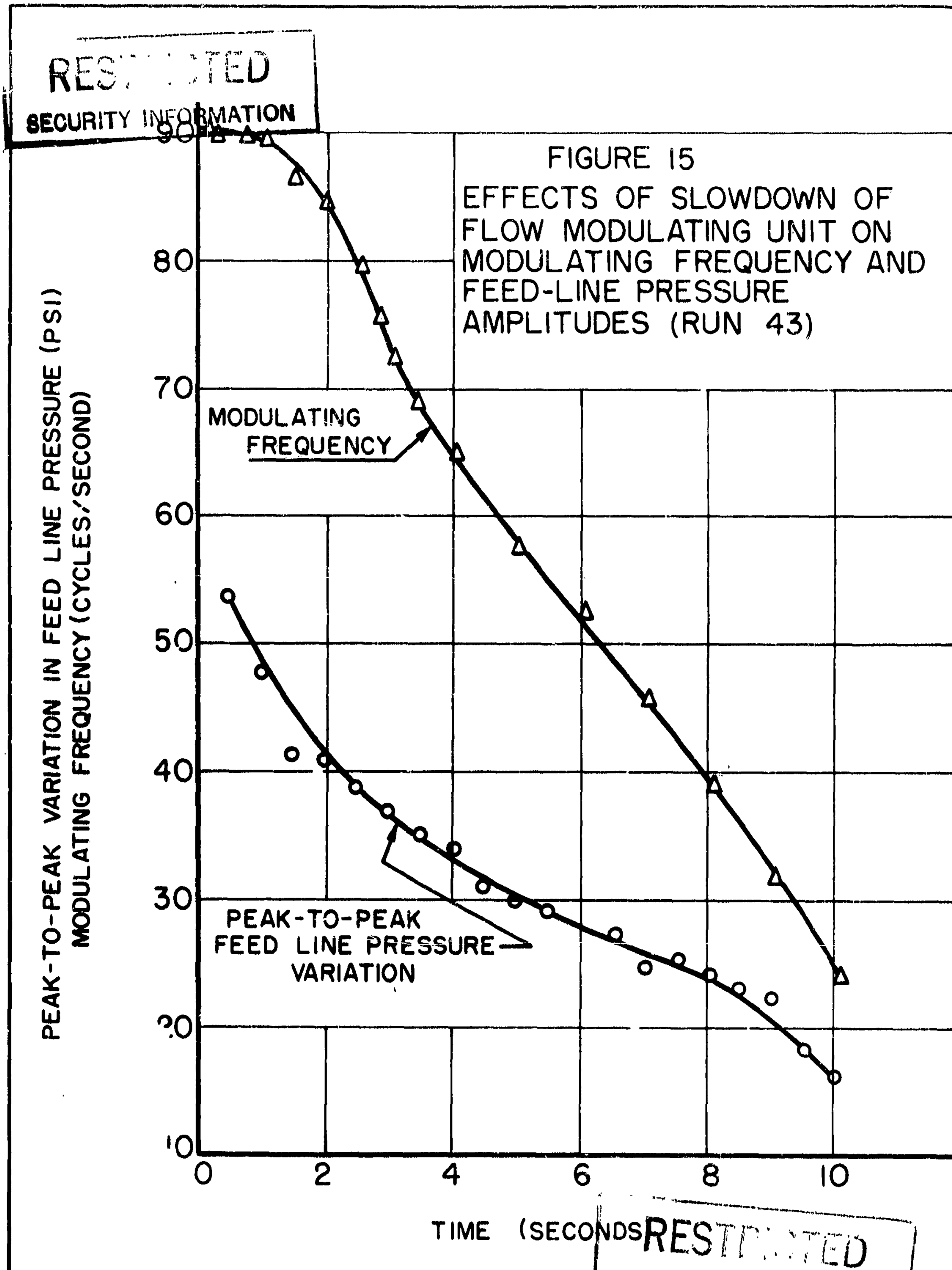
FIGURE 15
EFFECTS OF SLOWDOWN OF FLOW MODULATING UNIT ON MODULATING FREQUENCY AND FEED-LINE PRESSURE AMPLITUDES (RUN 43)
MODULATING FREQUENCY
PEAK-TO-PEAK FEED LINE PRESSURE VARIATION
PEAK-TO-PEAK VARIATION IN FEED LINE PRESSURE (PSI)
MODULATING FREQUENCY (CYCLES/SECOND)
10
20
30
40
50
60
70
80
90
0
2
4
6
8
10
TIME (SECONDS)

APPENDIX A

"AN INVESTIGATION INTO THE POSSIBILITIES
OF ADAPTING THE HOT-WIRE ANEMOMETER TO
LIQUID PHASE MEASUREMENT"

TABLE OF CONTENTS

FIGURES

INTRODUCTION

When dealing with liquid flow, one is often confronted with the problem of instantaneous mass measurement of a periodic flow variation. Often, too, the additional problem of size and location of the measuring device is of prime importance if the correct phase of the periodic flow is to be determined. Such a situation presents itself in the measurement of instantaneous mass of propellant flowing into a rocket motor, where the concern is for the point of measurement to be as near as possible to the injector orifice. For the lower frequency cases, below 100 cycles per second, recently developed flow meters (Ref. 1) are capable of indicating the mass fluctuations, but due to the relatively large dimensions of the sensing elements of these devices a phase correction is necessary at the specific point at which measurement is desired (see Appendix A). Phase correction made theoretically using the characteristic speed of wave propagation in the particular liquid in question would prove insufficient in all but the simplest system configurations due to variables such as dissolved gas in the liquid, line elasticity, and the geometry of the system. In order to determine this phase correction a new measuring device is called for.

Confronted with a similar problem in gases, one would turn to a hot-wire anemometer. Attention was turned to the possibilities of adapting such a device to liquid flow measurement. Characteristics of the air hot-wire anemometer which would fulfill the liquid measurement requirements, provided, of course, a liquid instrument could be made to work, include the ability to pick up high frequency flow fluctuations, small probe dimensions, and dependability of operation brought about by the large amount of previous work devoted to improving its performance. Since the basis of the hot-wire anemometer operation is that of sensing the varying ability of the measured moving fluid to remove heat from the higher temperature wire,

THEORY

A clearer picture of some of the possible variations between the air and liquid systems may be had by referring to the basic hot-wire equations. Starting with King's equation which relates the heat loss per unit length of wire, H, to the fluid heat transfer properties times the change in temperature we have:

$$(1) \qquad H = (a + b\sqrt{V}) \quad (T - T_f)$$

where T is the wire temperature, T_f is the fluid temperature, V is the fluid velocity, a is the constant connected with radiation and free convection, and b is the forced convection constant.

Taking an energy balance in the wire, the energy stored is equal to the incoming electrical energy minus the heat losses or:

$$(2) \qquad \frac{dH}{dt} = i^2R - (a + b\sqrt{V}) \; (T - T_f)$$

where i is the current through the wire and R is the instantaneous wire resistance (Ref. 2).

Using equation (2) and the expression:

$$(3) \qquad \frac{dH}{dt} = 4.2ms \frac{dT}{dt}$$

which relates the increase in the energy of the wire to the increase in its temperature, where m is the mass of the wire and s is the specific heat of the wire, Dryden (Ref. 3) showed that a heated wire experiences a phase retardation $\phi = \arctan M\omega$ ($\omega = 2\pi$ frequency) while the amplitude is reduced to $1/\sqrt{1 + M^2\omega^2}$ of the original value. M is the time constant for a heated wire at a given heating current and operating temperature and has the dimensions of time. It is related to the other parameters as follows:

$$(4) \qquad M = \frac{4.2ms\,(\bar{T} - T_f)}{i^2 R_f}$$

where $\bar{T}$ is the average temperature of the wire and the subscript f indicates the condition at fluid temperature (Ref. 2).

Using equation (4) some idea of the relative magnitude of the time constant in the liquid case considering the wire alone can be seen from the following example. Using a probe of .002 inch diameter nickel wire (many times larger than the air hot-wire due to necessary strength considerations), .2 inches in length, in water of temperature 20°C with wire heating current of 1.5 amp.*, if we assume the wire reaches a temperature of 70°C** for 70 feet per second flow we find that M is of the order of .005 seconds. Although this value is several times greater than the time constant associated with air hot-wire anemometers, which are of the order $.001 < M < .002$ seconds for corresponding air speeds (Ref. 2), it is, however, of the same order of magnitude, and further current increase would tend to make the difference even smaller. Therefore, the characteristics of the hot-wires operating in gas and liquid media are seen to be essentially the same.

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* Based on experimental data.
** Approximation based on heat transfer data of nickel wire in water.

LIQUID HOT-WIRE ANEMOMETER

We shall now consider the actual physical makeup of the liquid apparatus used.

To fulfill the phase measurement requirement, a very particular hot-wire anemometer was necessary. In the frequency range below 200 cycles per second in which we are interested, even the fine wires operating in air have to be compensated for a wire time lag. In this frequency range and higher, the larger wires anticipated for use in the liquid flow measurement would certainly require compensation. Investigation into the various systems which would fulfill this requirement showed that the electronic circuit of the hot-wire equipment used by the NACA at the Lewis Flight Propulsion Laboratory offered the most promise as a basis for possible liquid work. This was due to the fact that the constant-temperature system as used by NACA operates the wire with continuous compensation due to a continuously varying feed-back voltage. With this method the greater part of the variation of current and resistance is removed by the use of a high-gain amplifier and appropriate bridge circuit which maintains the wire resistance and hence the wire temperature practically constant. Using this system, the equipment has a frequency response in air on the order of 40,000 cycles per second, while the voltage feed-back compensates for a time lag in wire response up to a range of 20,000 cycles per second. The standard constant-current type hot-wire anemometer, on the other hand, seldom exceeds 10,000 to 20,000 cycles per second in response, and requires compensation to make it useful as a phase measuring device at all but the lowest frequencies (Refs. 4 and 5).

In selecting the material for the probe wire the following factors were taken into account:

1. Strength and durability
2. Sensitivity
3. Ease of handling

In considering tungsten, nickel, and platinum as three possible wire materials, the following table is informative:

Material	Tensile Strength (lb/sq. in.)	Electrical Resistivity (micro ohm-c,.)	Temp. Coefficient of Resistance (ohm-cm./°C)
Tungsten (hard)	590,000	5.51	.0045
Nickel (hard)	155,000	7.8	.006
Platinum	50,000	10.0	.003

Based on 20°C, Reference 6

Tungsten is seen to far surpass the other two metals as far as strength is concerned; however, when considering durability the fact that tungsten is susceptible to oxidation would prove a decided disadvantage if extended repeatable operation is considered. Nickel would seem a logical second choice in this category. Concerning sensitivity, both high temperature coefficient of resistance and high resistance are desirable. It is seen that the temperature coefficient of resistance of the nickel wire is one third greater than that of the tungsten, an important advantage. The actual resistance of a given length of wire is determined from the relation: $R = \rho l/A$, and since for a given application the relative strengths determine the wire area, A, the resistance for a given length, l, is a logical comparison of the relative merits of the wires. Thus, although the resistivity of tungsten is the lowest, it would prove the best choice, with nickel second. Another look at equation (4) reveals that tungsten would have the advantage on a minimum time constant basis. Considering the practical aspect of ease of handling we find that from this standpoint the advantage lies with nickel and platinum, since both can be soft-soldered, while tungsten requires welding or plating before soldering to attach it to the wire supports. Since we are working with liquids, high sensitivity is required, and oxidation might hinder the ability to reproduce results. Furthermore, plating and precision welding facilities were not available, and so nickel was chosen over tungsten as the probe material.

The wire sensitivity can be further increased by the proper probe design. As has already been seen from equation (4), the smallest wire diameter possible for the limiting operating conditions is desirable due to high R and low m considerations. Using the probe dimensions, namely the limiting distance separating the wire supports, as the basis for determining the wire size, tests were conducted which demonstrated that the .002 inch diameter wire withstood the flow conditions without breakage. Smaller wires may be used with similar flow speeds if initial flow surges are not a factor to be concerned with as was the case in this particular application.

With the wire material and size determined and the maximum current limited by surface boiling (surface boiling caused signal disturbances), the problem of increasing the sensitivity of the probe required further consideration. Again using equation (4) as a design basis it is seen that the sensitivity can be increased while m remains fixed if we lengthen the wire (since m is proportional to R for a given diameter wire). Of course, this still necessitates wire support at the same interval if the wire is to remain intact. This was accomplished by coiling the wire around two fixed plastic-coated probe supports. The probe supports used extended from the electrode and ground on a modified model spark plug. The plug serves as a pressure seal when the probe is seated in the housing, where the housing also serves as a part of a rocket propellant injector assembly (Fig. 1).

Concerning other components in the system, the auxiliary current supply was made similar to that proposed by NACA. However, suitable changes were made to provide the magnitude of current necessary in our application (see Fig. 2 for the diagram of the bridge and auxiliary current supply). In the amplifier itself a pair of trimmers were substituted for the fixed condensers as noted by the asterisks in Fig. 3. This change made possible a better balancing of the two halves of this push-pull type amplifier. A second change was made in the manner of bridge balance indication in that a Millivac variable-range voltmeter was substituted for the galvanometer used by NACA. Other than these changes the circuit remained the same as that used in the air operation (see Fig. 4 for photo of entire apparatus).

In order to test the operation of the probe, bridge, constant temperature hot-wire amplifier, and auxiliary current supply, when operating as a unit a small a.c. signal was fed into the bridge and the resulting output signal was measured with the amplifier on and off. The ratio of the two signals gave a measure of the amplifier characteristics in the final circuit. A comparison of these results with the original NACA circuit is shown in Fig. 5. The two curves show a very flat response characteristic for a considerable frequency range above the range of interest. The higher amplification of our system is due to the increased amplifier setting (150 ma versus 80 ma for the NACA test), this being the range used during the operation of the equipment.

METHODS OF CALIBRATION

Several methods were used in an attempt to determine the hot-wire time lag in actual liquid operation. The first method tried utilized the arrangement shown in Figs. 6a and 6b. This consisted of a small high speed motor (maximum 5,000 rpm) driving an 8 inch diameter disc on the rim of which was attached a one sixteenth inch chord "double wedge shaped" pin. This pin interrupted the flow of water periodically. The hot-wire probe (a single wire probe was sufficient on a signal amplitude basis in this case) was mounted in the water stream below the disc. Above the disc was mounted a photoelectric cell unit and a light source. Light was reflected from a mirror located on the upper surface of the disc causing the photoelectric cell to operate periodically. The position of the mirror and the water stream was adjusted in a static condition such that a signal was sent by the photoelectric cell to a dual-beam oscilloscope whenever the stream was interrupted by the pin (the exact setting having been made when the pin was directly above the single-wire probe). Knowing the starting point of the flow discontinuity, the water velocity (which was determined by flow measurements and the area of the flow tube as shown in the calibration curves of Fig. 7), and the distance between pin and hot-wire, we then have the expected time for the hot-wire response. Any displacement of the hot-wire signal would represent the lag of the wire.

The width of the pin was kept to the order of 1° of the circumference of the disc in order that the signal could be precisely determined. A rectangular cross section stream was used to eliminate the effects of the pin as it entered and left the circular stream before arriving at a position directly above the hot-wire (see Fig. 8). This system met with difficulty at times due to turbulance along the edges of the less than .05-inch width stream, producing a great number of random signals. Exact placement of the probe, however, allowed a number of satisfactory runs.

A second approach to the problem was that of introducing a velocity distribution as close as possible to a step function in the liquid flow. The equipment used to produce such a flow (see Fig. 13) consisted of a known weight striking a piston with a known velocity which induced a nearly impulsive velocity to the piston itself. Since the piston was immersed in a water filled cylinder, the impulsive motion transmitted to the liquid caused propagation of liquid waves from the piston surface. The waves traveled the length of the larger cylinder and were reinforced as they entered the smaller diameter tube leading to the hot-wire probe. The probe used in this system was described previously on pages 7 and 8.

There were two principal efforts in this case: 1) to determine the exact time the wave was originated and, knowing the water distance, to compare the wave arrival time with the signal which was sent from the hot-wire probe; 2) to analyse the shape of the resulting signal.

In order to fulfill the requirement that the initiation of the wave could be precisely known a simple electrical contact was devised in a circuit with a small six volt light. An appropriate size condenser was included to suppress the tendency for arcing as the contact was broken. Using a jeweled indicator, the amount of movement was shown to be two ten-thousandths of an inch to open the circuit. Later high speed photographs showed that any arcing was plainly visible, so that the origin of piston movement was readily determined by this method (see representative photograph Fig. 14).

In order to keep the force imparted to the system by the falling uniform and reduce vibrations, a metal block was centered on the upper end of the piston (see Fig. 13). This kept the point of contact directly above the piston rod. Two blocks were used: a lead one for an inelastic type collision, and a steel block for the elastic type collision and a steeper velocity gradient in the resulting liquid flow.

A third method used in determining the hot-wire time lag was that of using a known periodic flow and comparing it with the resulting periodic hot-wire signal. The equipment used for these tests is shown in Fig. 20a and the accompanying diagram, Fig. 20b. The pre-modulated flow was kept constant with a cavitating venturi (Ref. 7). A pulsing unit consisting of a small high speed piston assembly driven by a variable speed motor was used to supply the sinusoidal variations in flow -- the exact phase of the flow being determined by a photoelectric cell, light source, and mirror combination operating off the flywheel. The hot-wire probe was placed in a line housing adjacent to the downstream fitting of this flow modulating unit.

With such a system, the effects of fluid compressibility and inertia were minimised due to the effect of the cavitating venturi in preventing upstream wave travel. The effects of line elasticity were negligibly small due to the short lines between pulsing unit and hot-wire probe. These conditions were necessary in order that the total phase difference between the periodic flow at the pulsing unit and the hot-wire signal would include only the hot-wire time lag and wave travel time.

Using the dual beam oscilloscope and high speed film technique, the total phase difference wa determined from the photoelectric cell and probe signals. The wave travel time was determined theoretically and hence a measure of the hot-wire time lag was obtained.

Water tests were also run with the hot-wire mounted in one of the rocket motor injectors, as shown in Fig. 20b. The resulting signal was similar to that obtained with the arrangement previously described, the only system difference having been in the type of probe housing and its location in the system.

DISCUSSION OF RESULTS

Typical data from the rotating disc method as produced on dual oscilloscope photographs by hot-wire and photoelectric cell signal traces are shown in Figs. 9, 10, and 11. Calibrations of the time intervals involved in this data were made by replacing the photoelectric cell signal with a 1000 cycles per second oscillator input (see Fig. 12). An attempt to measure the time between signals using a Berkeley Eput meter (an electronic counter which records the number of signals over an adjustable base time period) was discontinued due to a number of stray signals originating in nearby high voltage equipment which influenced the time records.

When the time required for the water flow discontinuity to travel from the pin to the hot-wire is superimposed on the photographic records (see Fig. 9) it is seen that the hot-wire signal originates with no measurable wire time lag. The time scale available from this equipment was apparently not capable of determining small order time lags. The shape of the hot-wire signal, however, in this circular stream case is spread over an interval of 3.3 milliseconds (60° of the 360° total between successive signals). This made it difficult to analyze exactly what was occurring during the inetrruption. Originally it had been expected that the angular duration of the signal would be of the same order of magnitude as the angle subtended by the pin on the disc. Replacing the circular stream flow (angle subtended equal to 2.5°) with the rectangular stream (angle 1°) it was found that the signal duration was reduced to 2.5 milliseconds (46°) while the point of the signal initiation remained the same as in the circular stream case (from the stream dimensions the difference in signal initiation would be .04 milliseconds which would not be discernable on this time scale).

This would tend to point to some change in the flow pattern about the wire which had been caused by the change in the flow stream dimensions. One possible explanation of what takes place assumed that liquid droplets remain briefly after the sudden flow interruption and thus the wire in boiling off the water requires a certain period to heat up rather than heating almost instantaneously as was first expected.

Further comparisons between the two shaped flow streams (see Figs. 9 and 10) shows that the reduction in signal duration was accomplished by shortening the time interval from signal initiation to maximum signal (from 1.9 milliseconds or 35° in the circular stream case to 1.1 milliseconds and 20° in the rectangular stream case) while the portion of the signal from maximum signal to its termination remained unchanged.

The photographic record of the smaller diameter wire (.001 inch) shows a similar signal shape and position (see Fig.11). The increased stream travel time indicated by this figure resulted from the necessity of using a lower liquid velocity in order to prevent breakage of the smaller wire.

Although these tests indicated that the hot-wire response was rapid, they were not conclusive insofar as wire time lag was concerned due to the signal width and limitation of the experimental equipment. To obtain quantitative results on the wire lag, another approach was needed, and the piston-impulse apparatus described earlier was constructed.

When the lead block was used in this apparatus (see page 11 and Fig. 13), the oscilloscope photographs of the hot-wire signal and electrical contact revealed an apparant hot-wire time lag of 1.0 milliseconds after the wave travel time had been subtracted from the total time delay (see Fig. 14). This was far in excess of that expected. The shape of the hot-wire signal was then analyzed, revealing that the major portion of the signal indicated the expected constant acceleration of the fluid, but that the initial portion of the signal was inconsistent from this consideration. The linear portion of the signal was extended to the base line in Fig. 14, and it was found that a time lag of but .15 $\pm$ .01 milliseconds would be present with such a signal shape. The degree of approximation to the desired step-function flow rate is indicated by the velocity-time trace of Fig. 19, which was taken with the hot-wire probe itself.

The steel block was next used under similar conditions of operation (see Fig. 16). In this case the flow more closely approached a true step function and hence initial velocity changes at the hot-wire were more abrupt. A comparison of similar runs with lead and steel blocks showed that the final velocity was reached in the steel-block case in less than one third the time required by that of the lead block (see Figs. 14 and 16). The deformation always present in the lead-block case was also eliminated. With this system the hot-wire time lag was shown to be .15 milliseconds, the same as the time lag predicted from the lead-block case.

In order to more closely simulate normal operating conditions, a steady flow of water was added to the system (see Fig. 13). In this way any possibilities of local static effects in the area of the hot-wire probe or accompanying electronic difficulties were eliminated. A typical record of the steel block system with steady flow is shown in Fig. 18. It is seen that the wire lag in this case is of the same order as or less than the wire time lag of the still-water steel-block case, although exact determination of the point or signal initiation is complicated by small flow disturbances in the fluid stream.

The ability of the probe to pick up flow changes is illustrated in

Fig. 17. This is a high amplitude signal which clearly shows wave phenomena in the accelerating portion of the fluid flow (still-water, lead-block test). These signals were due to the successive wave reflections off the ends of the water-filled cylinder. The wave signal spacing was of the order of .1 milliseconds, which corresponds to a speed of sound in water of 5,500 feet per second as determined from the cylinder dimensions. This wave speed is approximately 8% greater than that used in the previous wave travel time corrections (Ref. 6).

The effects of the amplifier in the system are seen by comparing a test made using the constant-temperature method (see Fig. 14) to a signal produced under the same test conditions with the amplifier off (see Fig. 15). Here it was found that the higher frequency flow signals were no longer visible, as was the case in the constant-temperature method, indicating a far lower frequency response. The hot-wire time lag in this case was 1.17 milliseconds with the fluid acceleration nearly linear throughout the signal duration.

From these sets of tests, the hot-wire time lag in water is seen to be of the order of .15 milliseconds. This would place the natural frequency of the system at 6,700 cycles per second which is considerably higher than that required in our particular application.

Using the third calibration method with the equipment as outlined on pages 11 and 12, it was found that when the probe was placed close to the pulsing unit the signal from the hot-wire was extremely distorted from the expected sinusoidal variation. A dual oscilloscope photograph of a typical test run is shown in Fig. 21, where the pips in the photocell signal indicate when the piston in the pulsing unit is at dead bottom in its stroke, while the hot-wire trace more closely resembles a saw-tooth wave. It was first believed that these poor results were due to the fact that the probe was located in a .25 inch inside diameter line which necessitated a rapid transition in line size (the upstream line size was .670" I.D.) and that the liquid wave reflections produced between the probe location and the cavitating venturi were a major factor in distorting the shape of the hot-wire signal. An attempt was therefore made to eliminate the line discontinuity by using a larger probe in a large line fitting (.60" I.D.). Even when the 75 cps signal was heavily filtered, however, (band width from 60 to 90 cycles per sec.) difficulty in removing extraneous signal frequencies was encountered, thus making any data inconclusive. No doubt turbulence and cavitation present in this highly disturbed section were major factors in producing such a distribution. Possible probe changes and increases in the pressure level of the system could conceivably improve the results but such tests were deemed inadvisable at the time since this method was intended to serve only as a check on previous results.

CONCLUSIONS

From the results obtained in the piston-impulse method of wire time lag calibration, the liquid hot-wire anemometer as used in these tests was shown to have a wire time lag of .15 milliseconds. This places the natural frequency of the instrument at approximately 6,700 cycles per second, which is quite sufficient for flow phase determination considerably in excess of the frequency of possible amplitude measurement available from current flowmeters. These characteristics may be improved by further development of probe design, the use of finer wires and higher current under less severe flow conditions, and an increase in the compensating ability of the constant-temperature amplifier. Further increase in the signal-to-noise ratio of the amplifier would also aid in improving the liquid signal wave shape, which is often affected by the high noise level.

Even in the present stage of development, however, the hot-wire anemometer holds considerable promise as a means of measuring the phase relationships in liquid flows due to its ability to pick up the higher frequency liquid flow variations. The small probe size possible constitutes a major advantage in this respect.

APPENDIX A

Factors that could be used in the evaluation of the determination of a flow signal are: 1) Amplitude, 2) Wave-form, 3) Phase, and 4) Frequency. In order to meet the requirement of true amplitude determination, considerations such as frequency response, attenuation, and stability of amplification would dictate the electronic system requirements. To determine the correct wave-form, additional factors such as non-linear distortion and the ability to reproduce the higher harmonics enter the picture. As far as phase and frequency are concerned, the band width and the amount of filtering in the electronic system are the factors that we are concerned with. It is with these criteria in mind that certain characteristics of three of the most modern flowmeters are briefly evaluated here.

Considering first the Mittelmann electronic flowmeter (Refs. 1 and 8) in its present stage of development, it was found that the instrument has a linearity of 1% which is reliable up to a frequency of 100 cycles per second. However, no phase relationships in the flow can be determined from this meter. The reason for the inability of equipment to give phase data is that the flow signal, which is superimposed on a 1000 cycle per second carrier frequency, is first passed through a narrow-band selective pre-amplifier. Since this narrow band is tuned to the 1000 cps range the higher and lower frequencies (the lower frequencies include those in the frequency response range of the meter) are considerably out of phase. This phase situation is further complicated by the phase shift in the main amplifier. If the signal is then passed through a rectifier to remove the carrier wave, the limit of reliable amplitude determination is further decreased due to the heavy filtering of the signal to approximately 40 to 50 cycles per second.

The Arnold meter (Refs. 1 and 9), through the use of a higher carrier frequency (5000 compared to Mittelmann's 1000), has a reliable response closer to 500 cps. The Arnold meter, however, is extremely sensitive to noise and vibrations due to the lack of the Faraday shielding present in the Mittelmann meter, and considerable zero drift is also present due to the low stability of the electronic system. These factors prevented the Arnold meter from reaching the amplitude accuracy exhibited by the Mittelmann device in the 0 - 100 cps range, although its over-all range is reportedly greater.

The third meter is the true-mass-rate flowmeter based on the Coriolis force principle (Refs. 1 and 10, Fig. 22). The frequency response of this instrument in its current stage of development is approximately 200 cycles per second. Practical considerations which limit this response are: 1) The radius of the sensing tube - the smallest possible tube is desired for high response but the accompanying high pressure drop limits the flow; 2) the deflection of the sensing element must be of a certain magnitude to allow strain gage detection; and 3) mechanical seal problems and vibration limit the motor speed and hence the limit of frequency response of the flow sensing element. Accurate phase determination of the fluid flow is complicated by the geometry of the flow passages within the meter, leading to difficulty in locating the exact point of measurement. Damping of the unbonded strain gage sensing element also might tend to create phase distortions. The simplicity of this design, however, would point to it as a possibly satisfactory flow measurement device in rocket testing.

All three instruments possess the highly desirable characteristic of a linear relationship between output signal and flow, i.e., the electromagnetic meters are based on flow velocity, while the Li flowmeter is based on mass flow rate. With any of these meters operating as close as possible to the point where flow measurement is desired, it is seen that the phase must be determined at the point by a separate means since all three fail to give sufficient phase data.

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FIGURE 1:
HOT-WIRE PROBES AND HOUSINGS
(1/4" AND 3/4" SIZES)

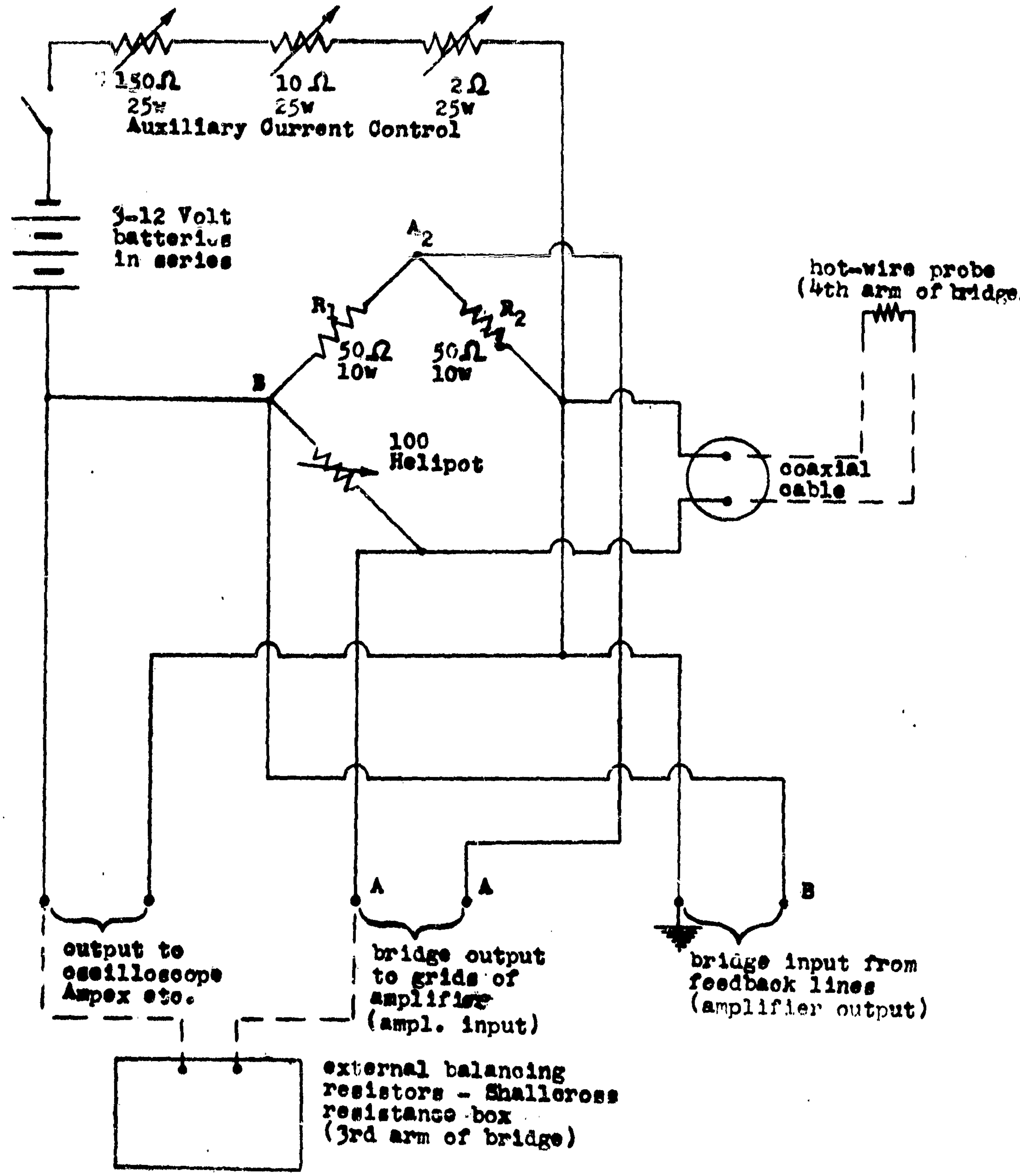


Figure 2. Diagram of the Hot-Wire Bridge and Auxiliary Current Supply

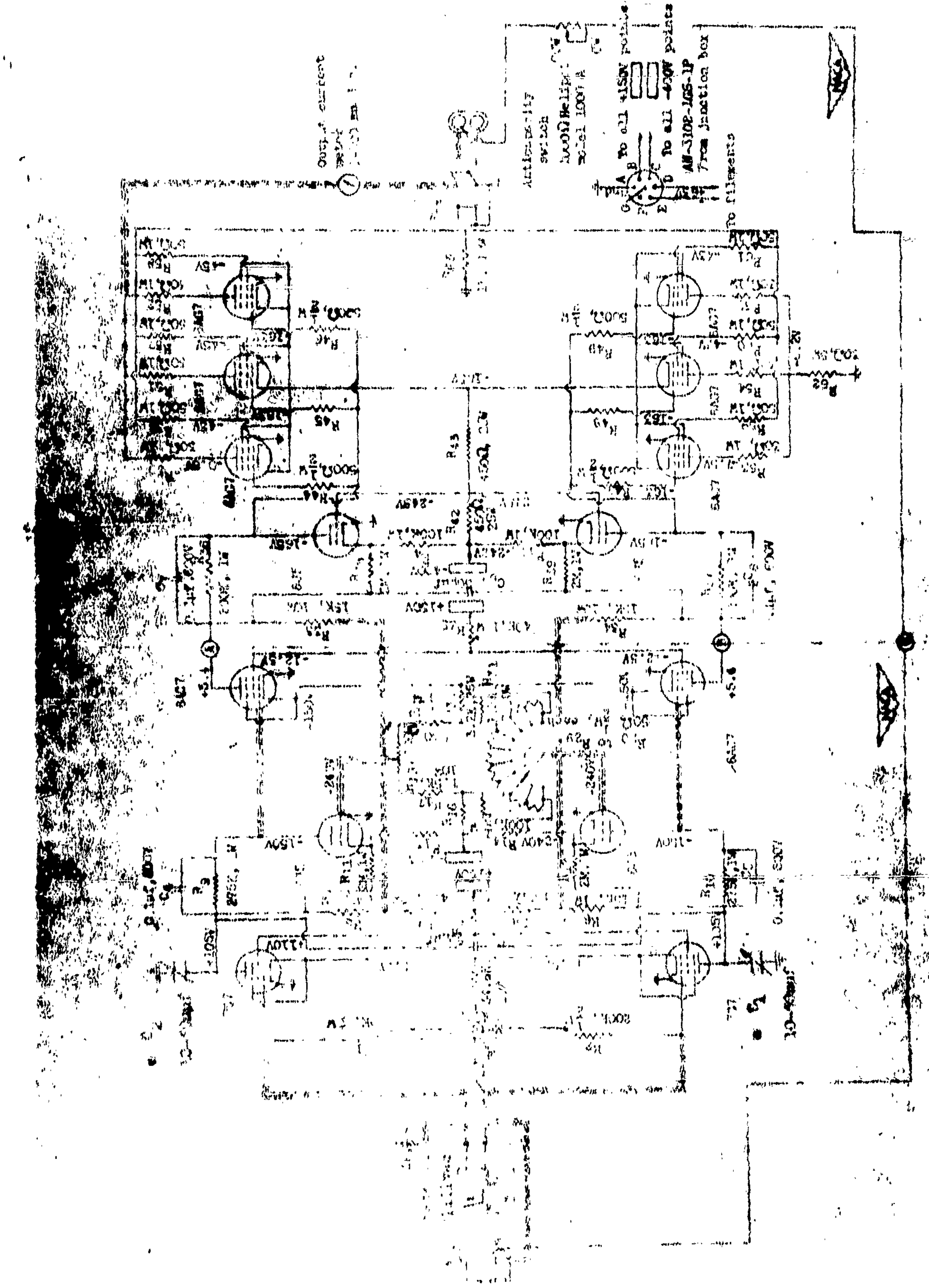


Figure 3 Constant temperature amplifier

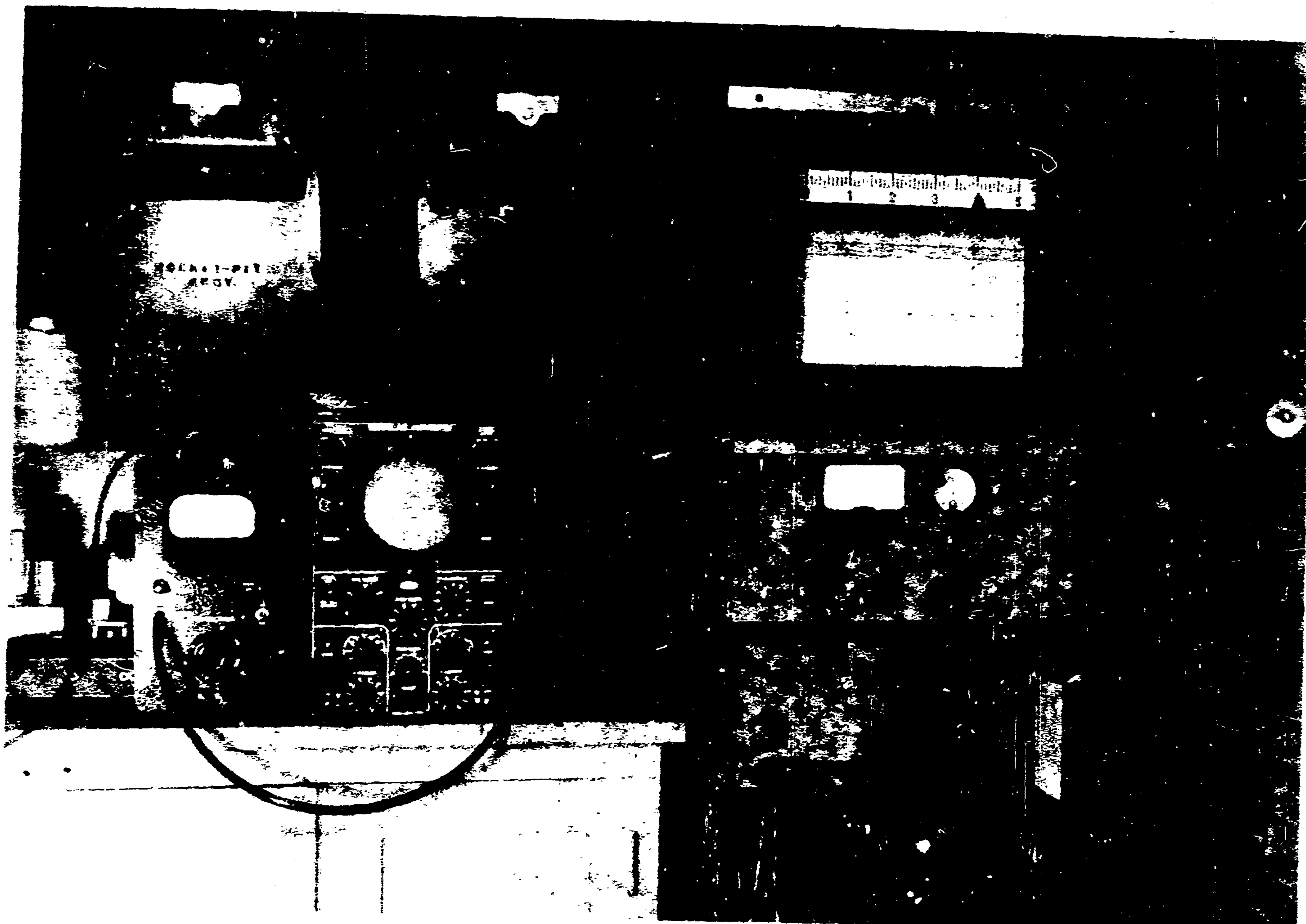
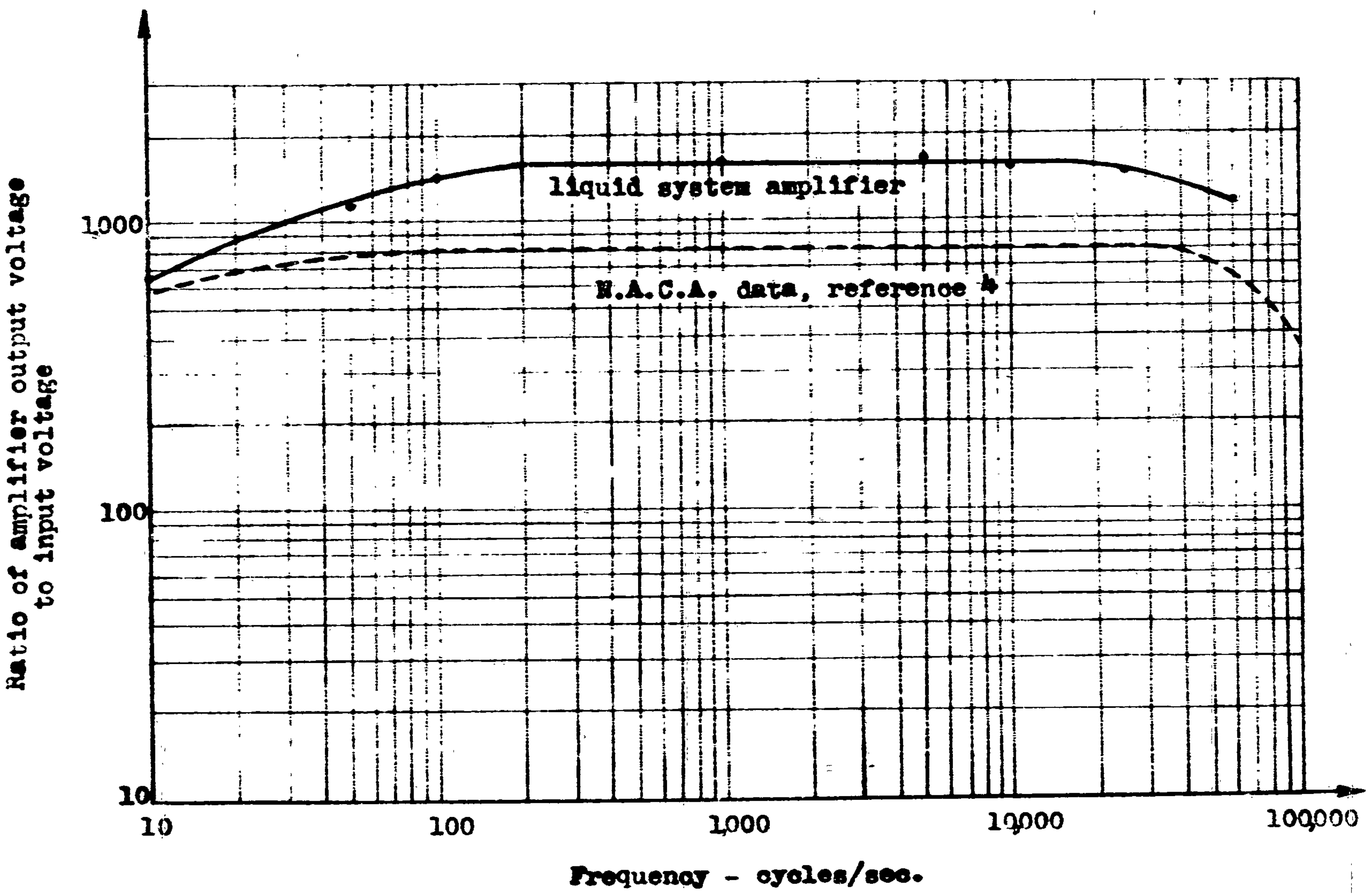


FIGURE 4
HOT-WIRE AUXILIARY APPARATUS



liquid system amplifier
N.A.C.A. data, reference 4
Ratio of amplifier output voltage to input voltage
1,000
100
10
10
100
1,000
10,000
100,000
Frequency - cycles/sec.

Figure 5

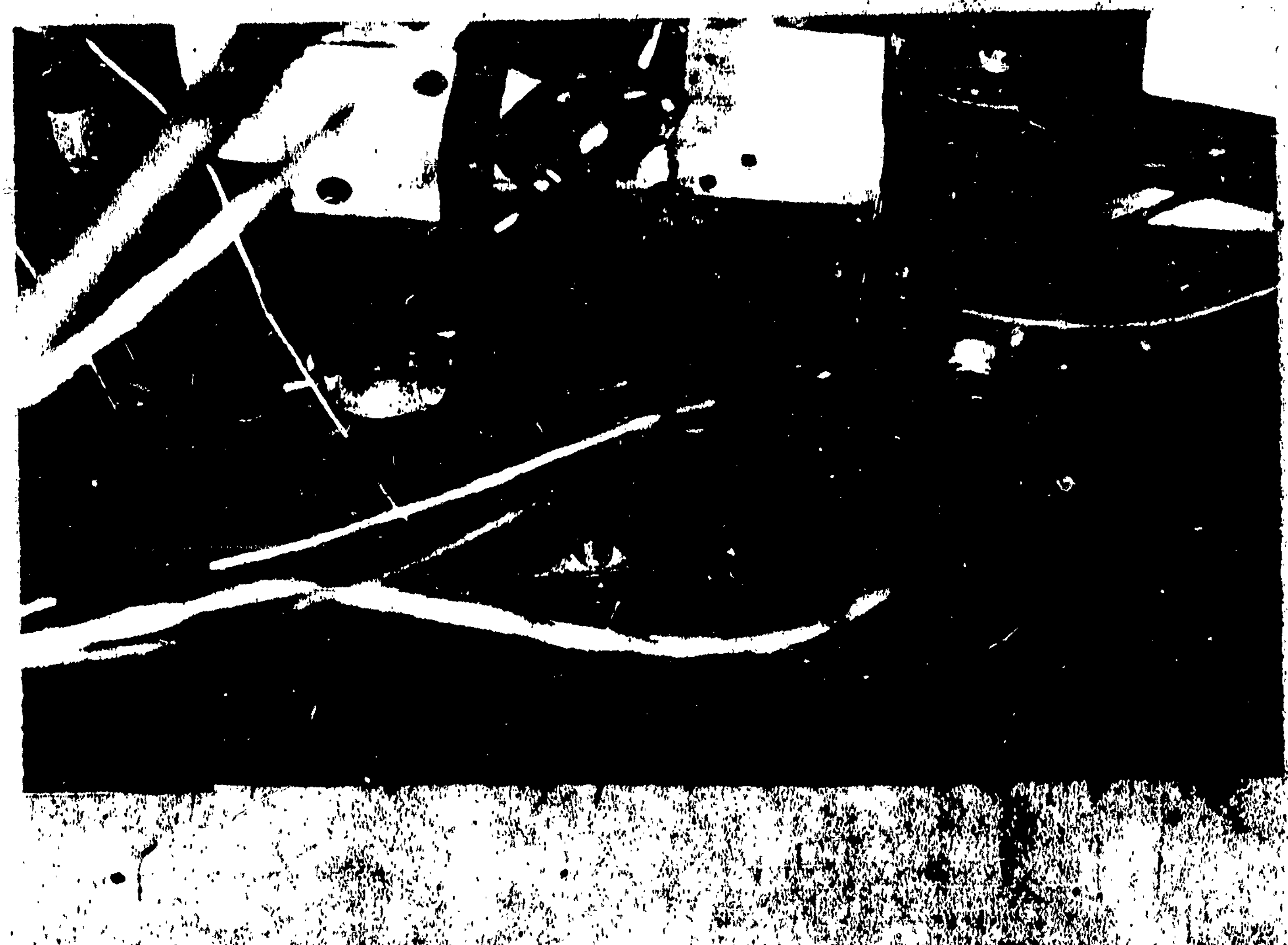


FIGURE 6a
VIEW SHOWING PIN, SINGLE-WIRE PROBES, DISC, AND MOTOR

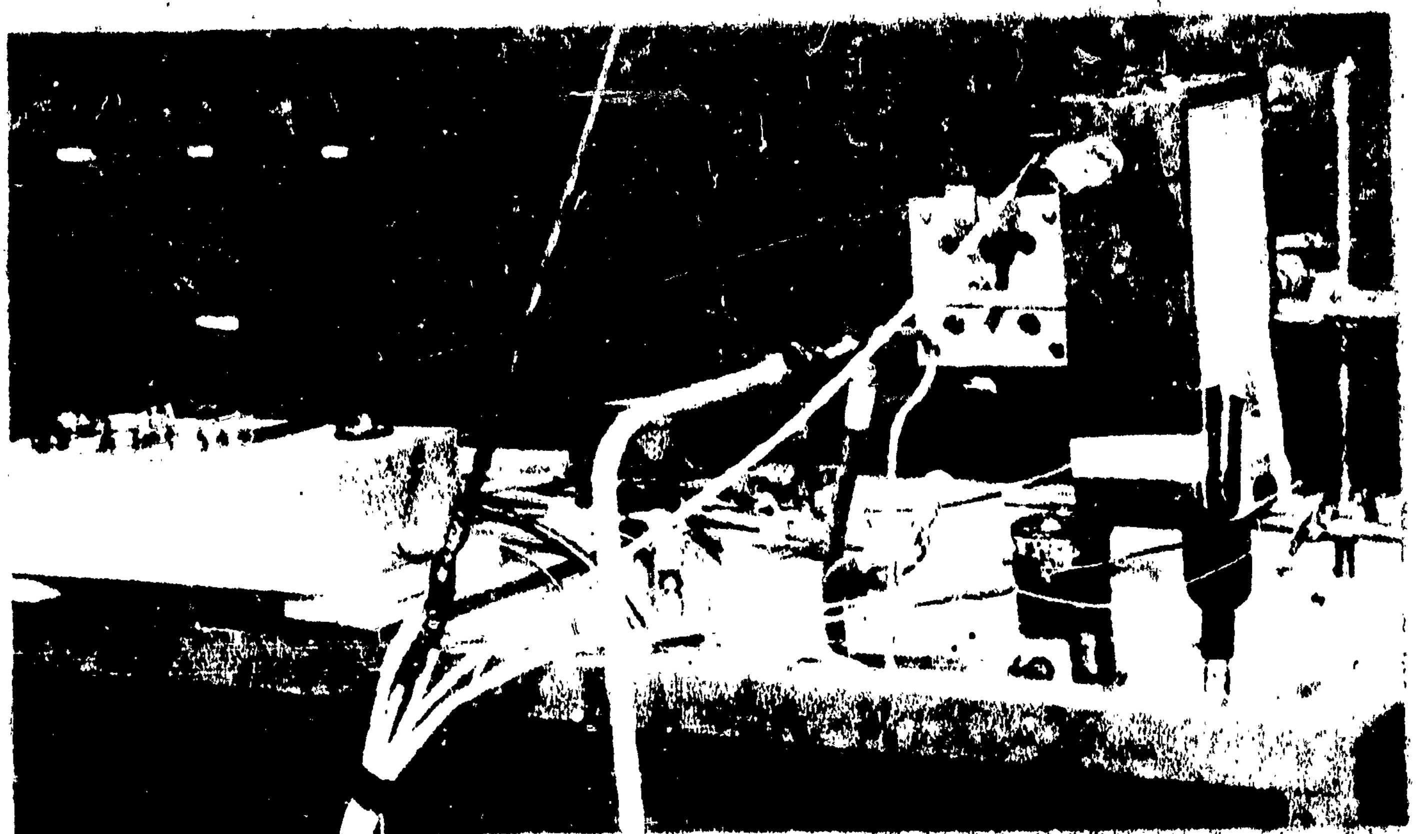


FIGURE 6b:

VIEW OF PHOTOELECTRIC CELL AND LIGHT SOURCE

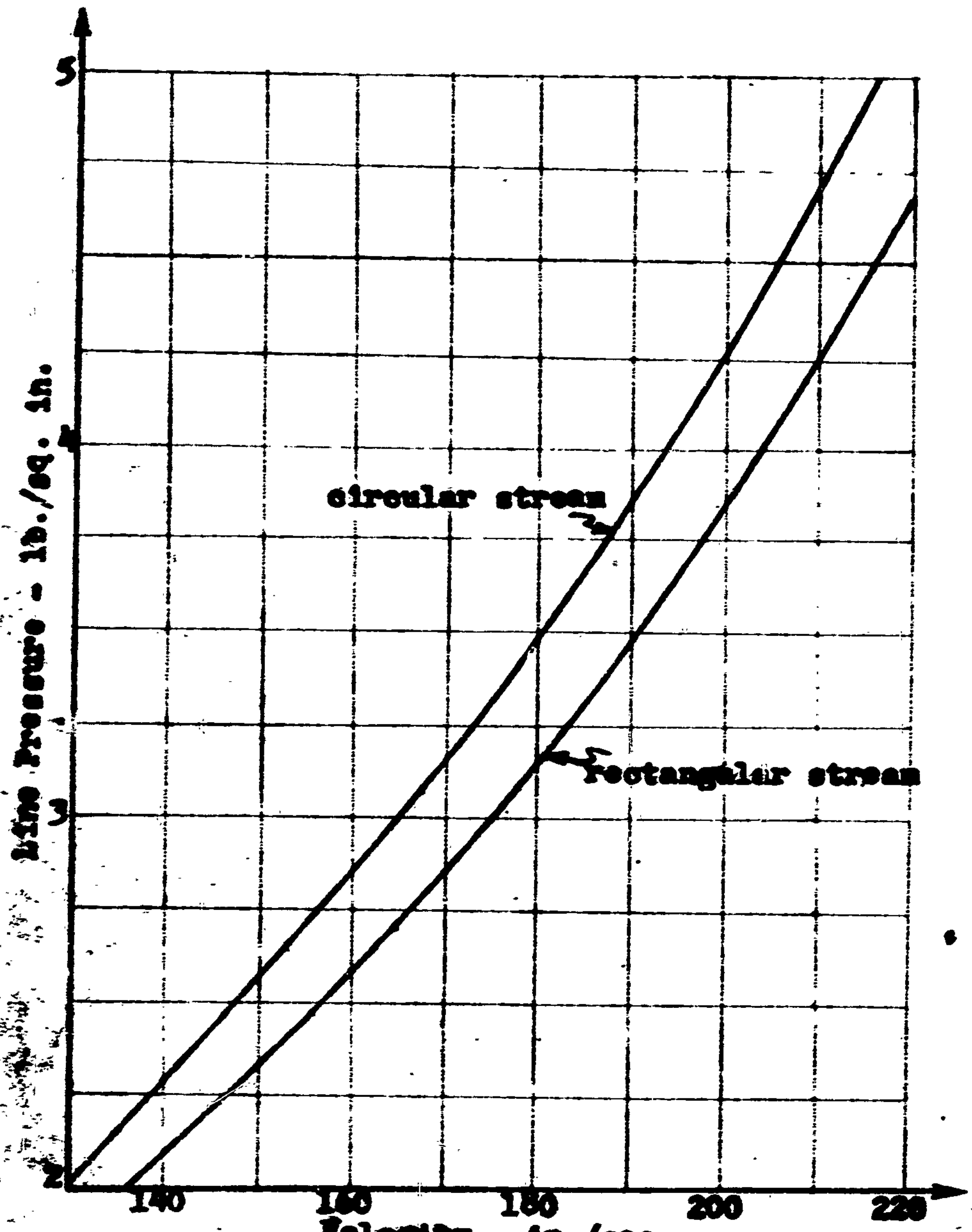


Figure 7

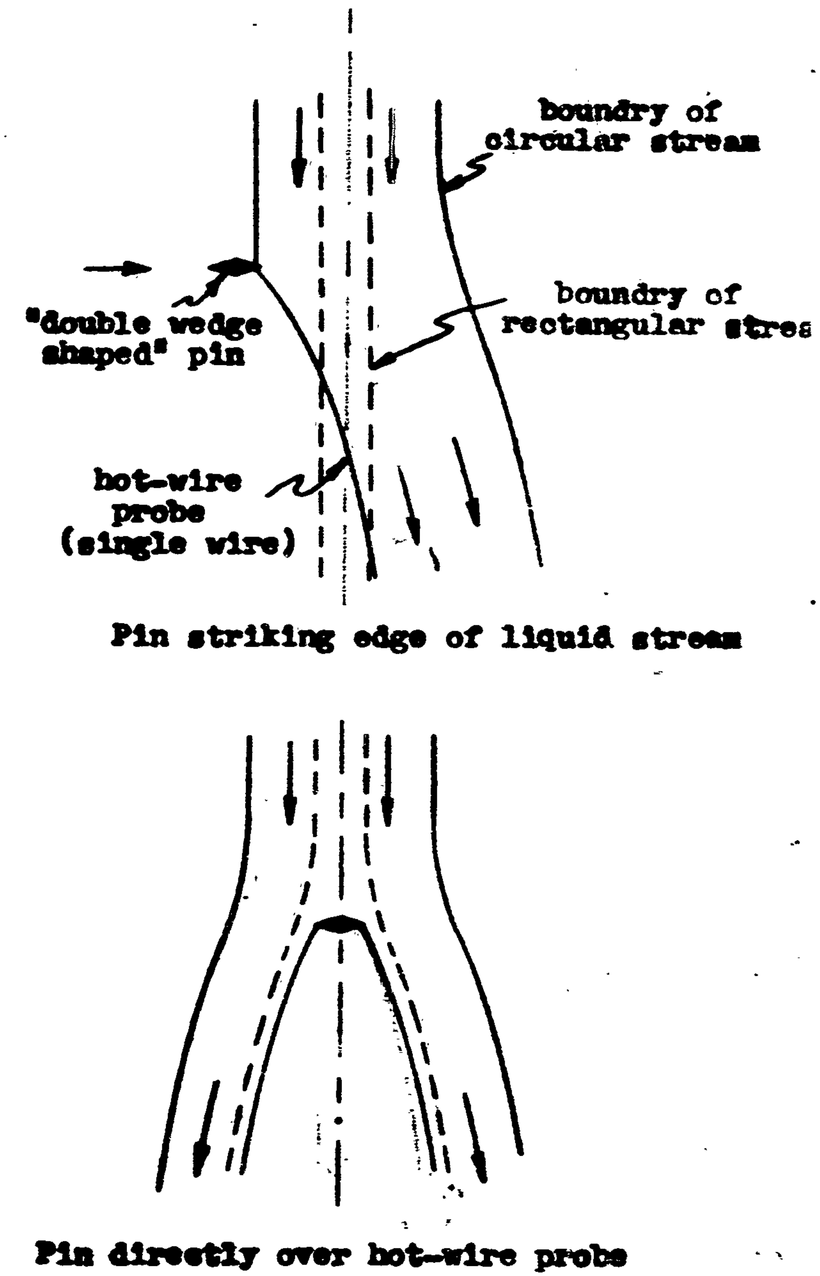


Figure 8

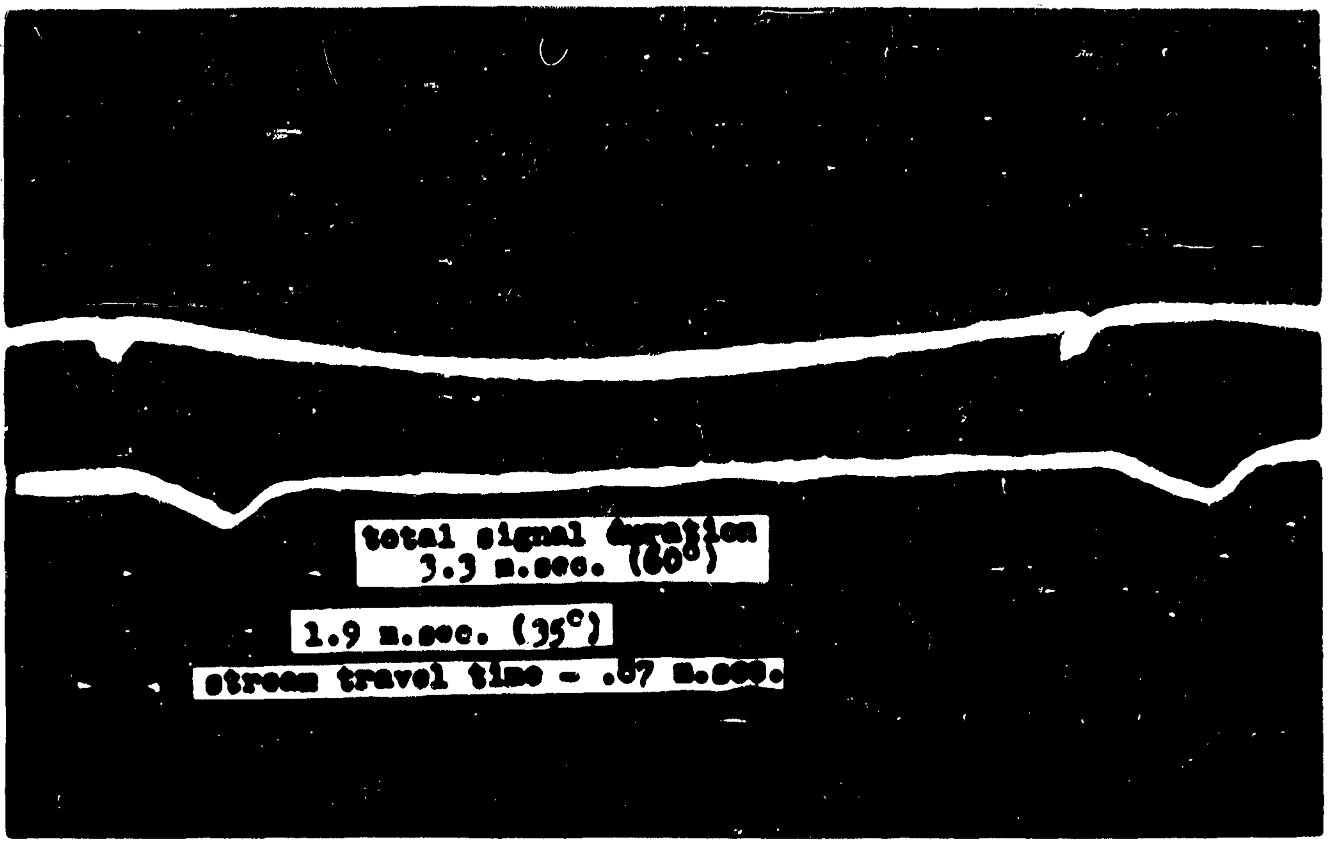


Figure 9. Circular Stream Case Using .002" Diameter Wire

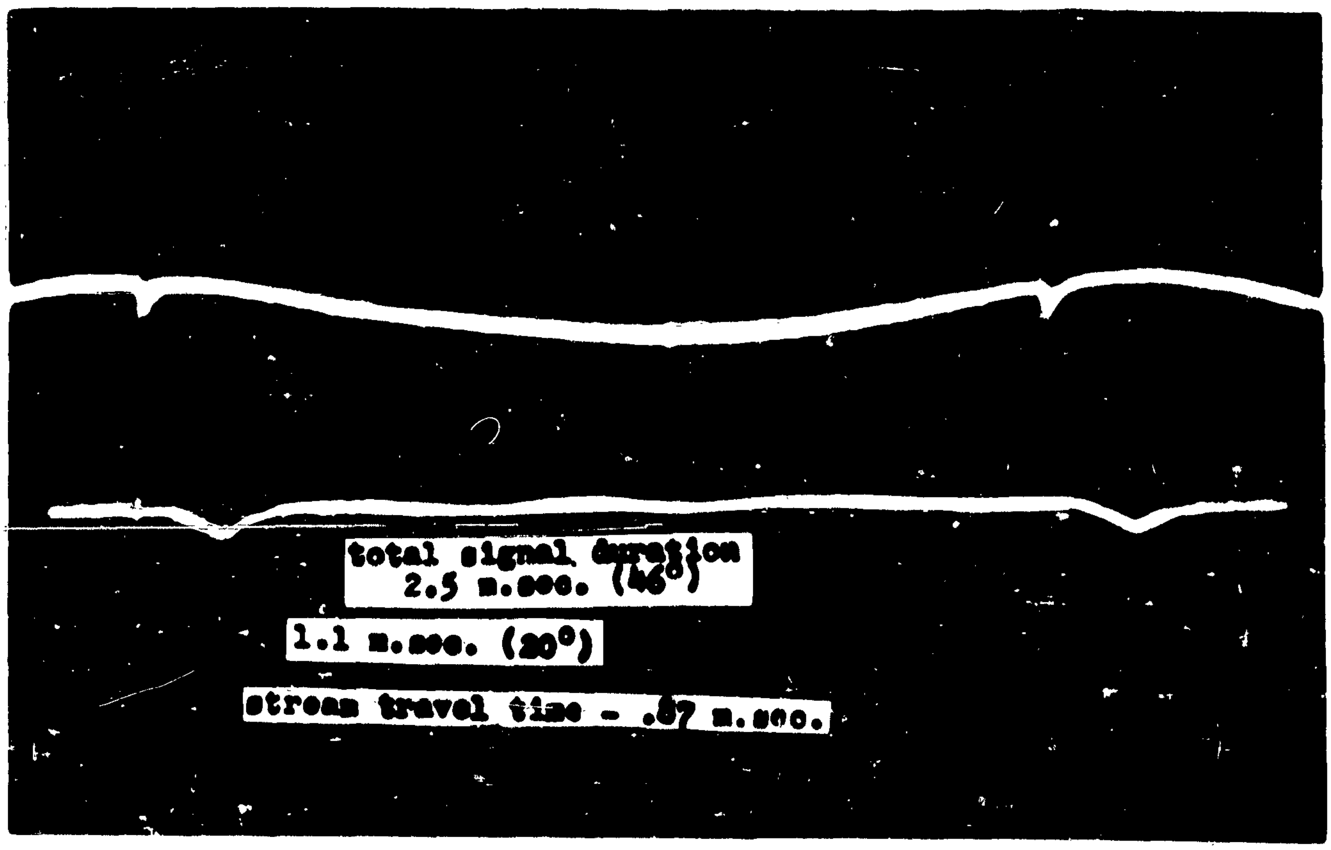


Figure 10. Rectangular Stream Case Using .002" Diameter Wire

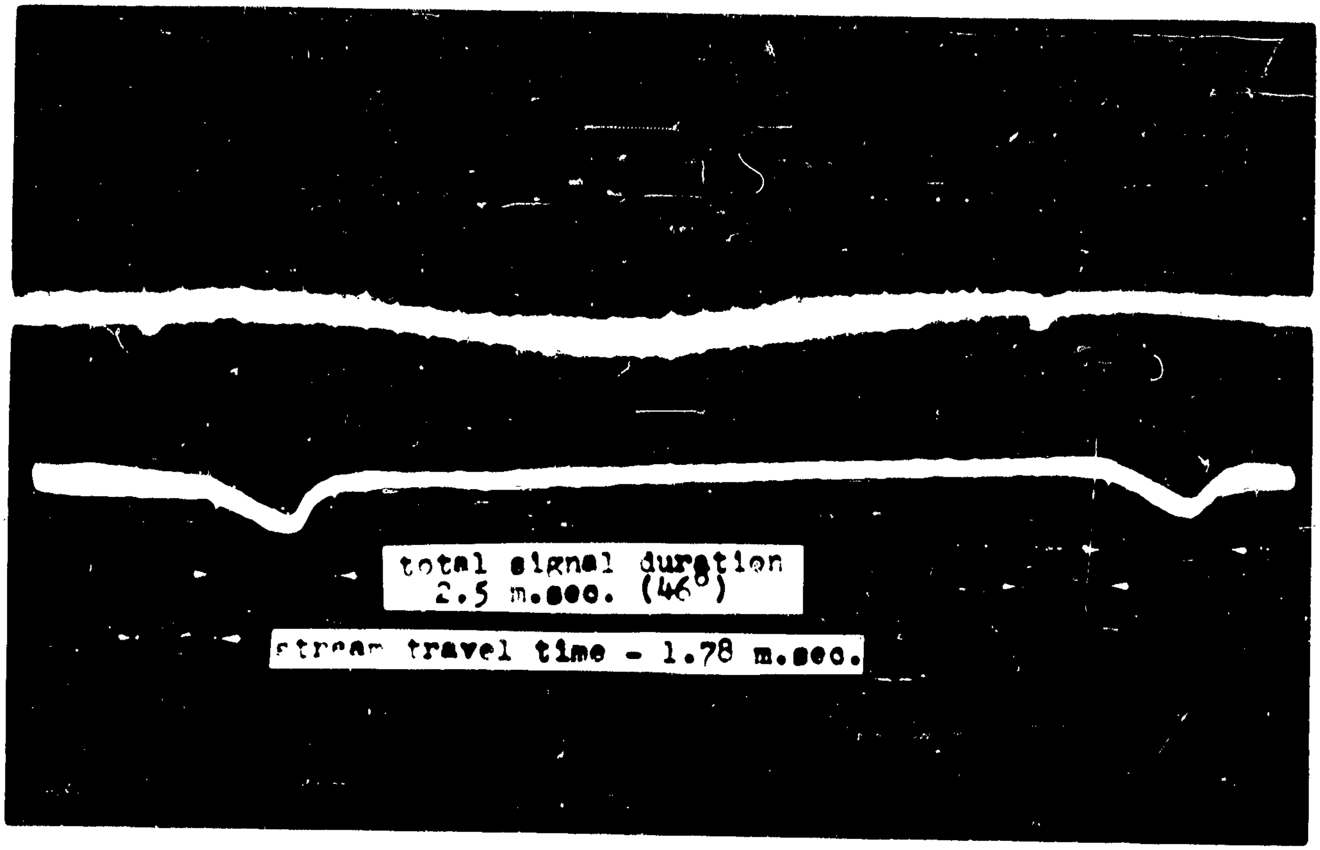


Figure 11. Rectangular Stream Case Using .001" Diameter Wire

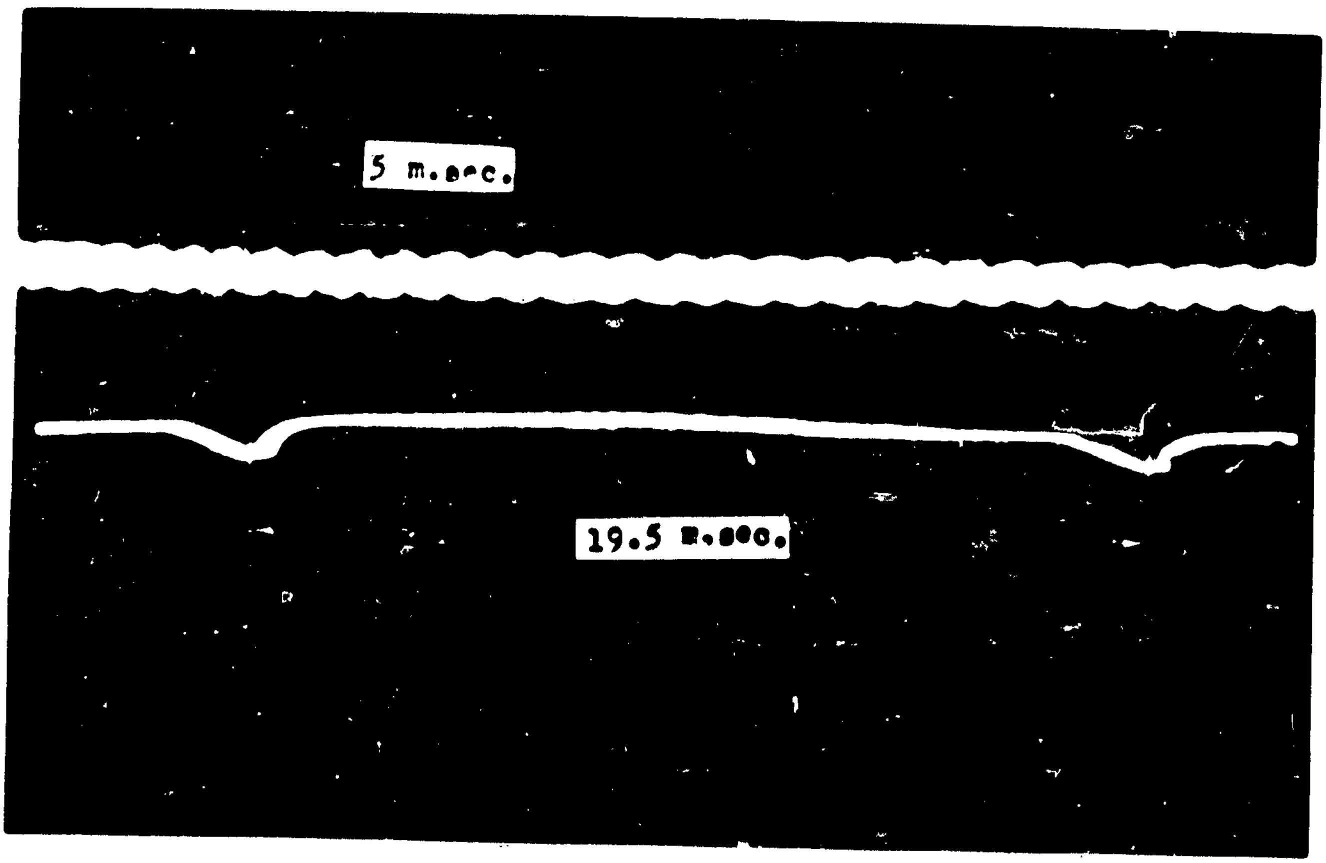


Figure 12. Rectangular Stream Case With 1000 c.p.s. Calibrating Signal

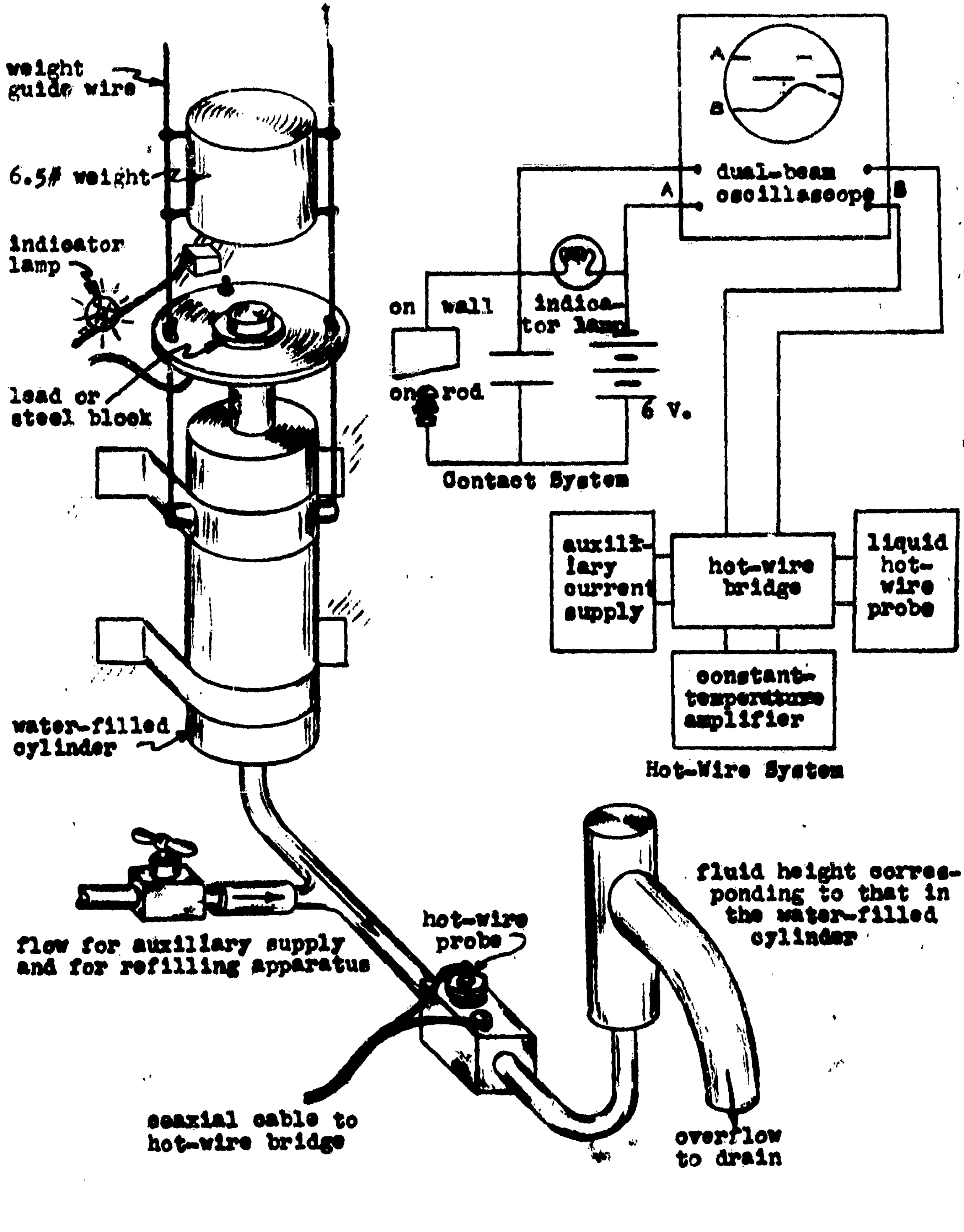


Figure 13. Diagram of Piston-Impulse System

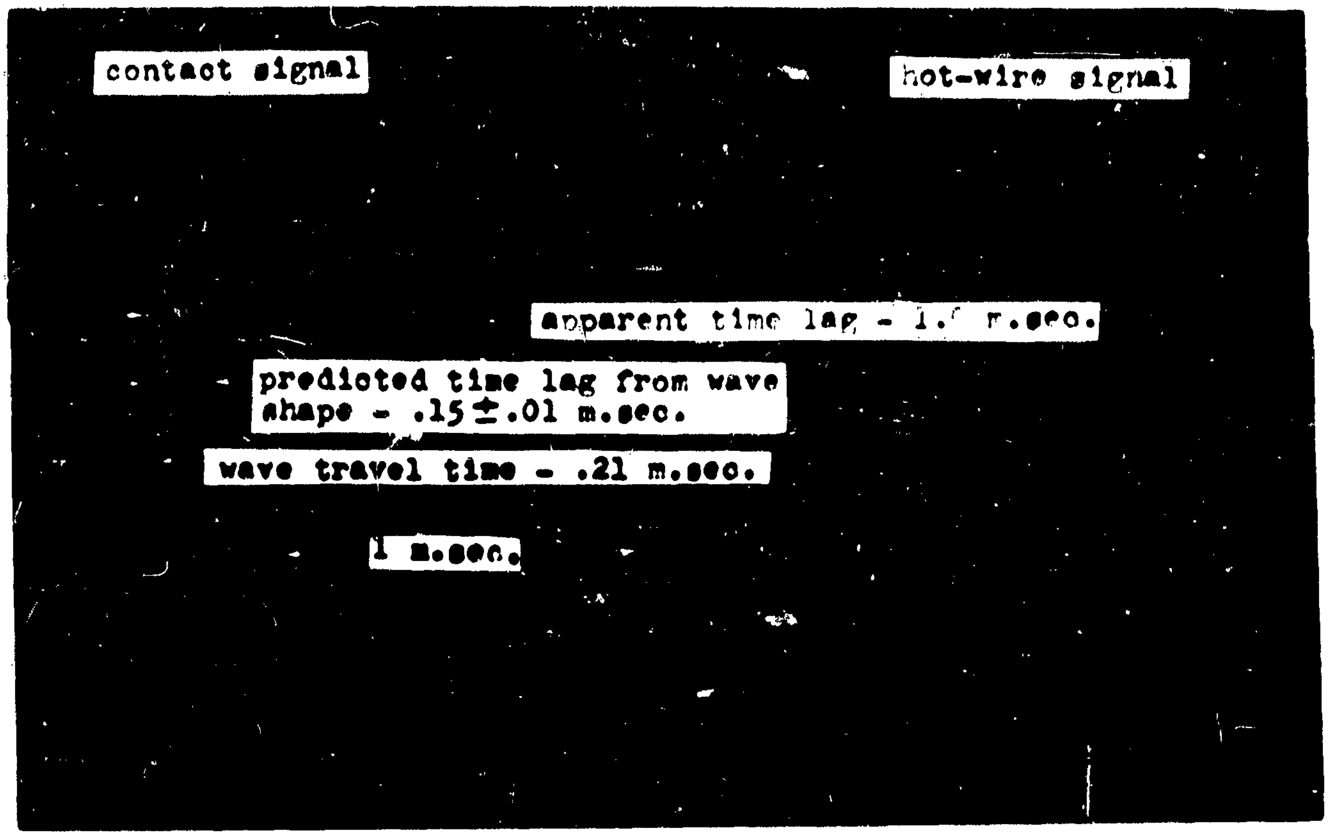


Figure 14. Piston Impulse Test, Still Water - Lead Case

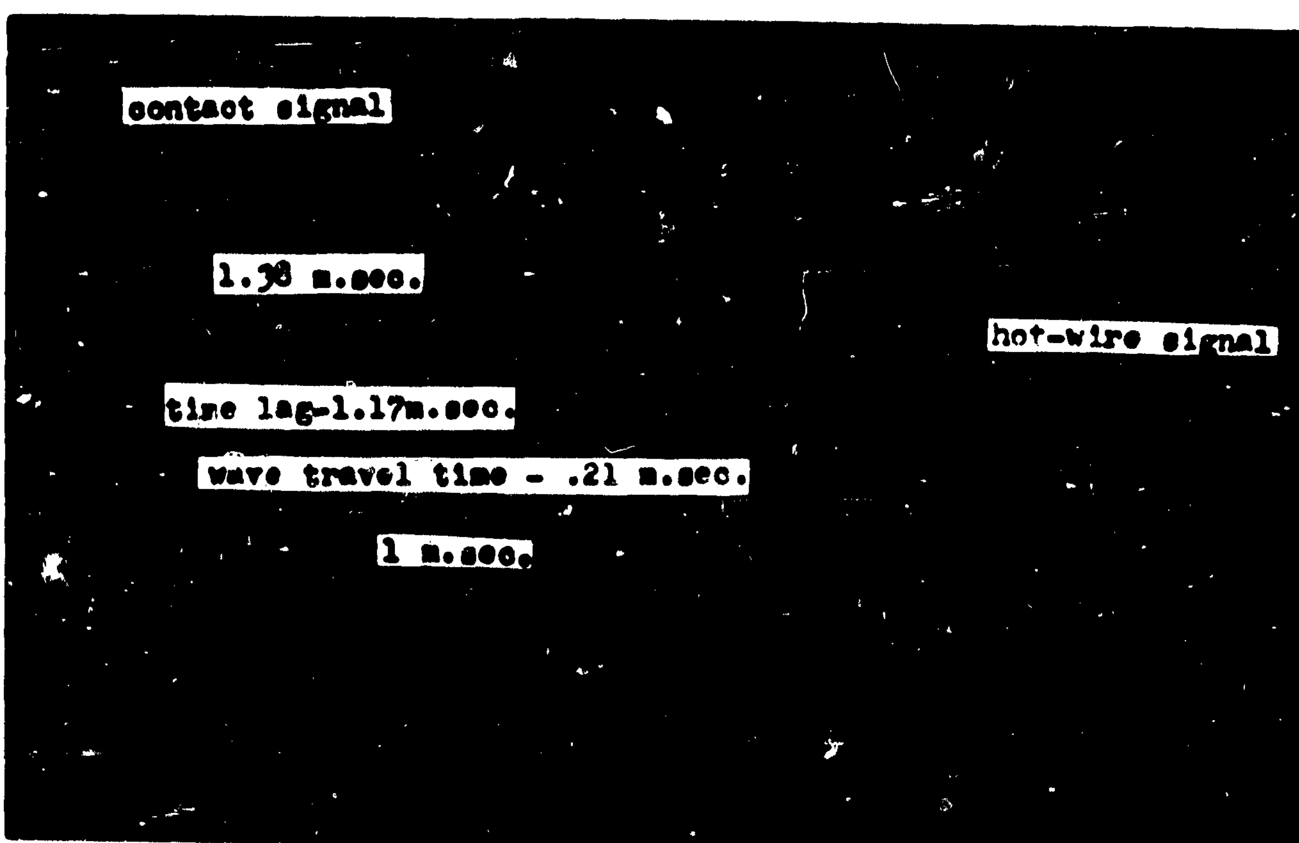


Figure 15. Same as Figure 14 Test With Amplifier Off

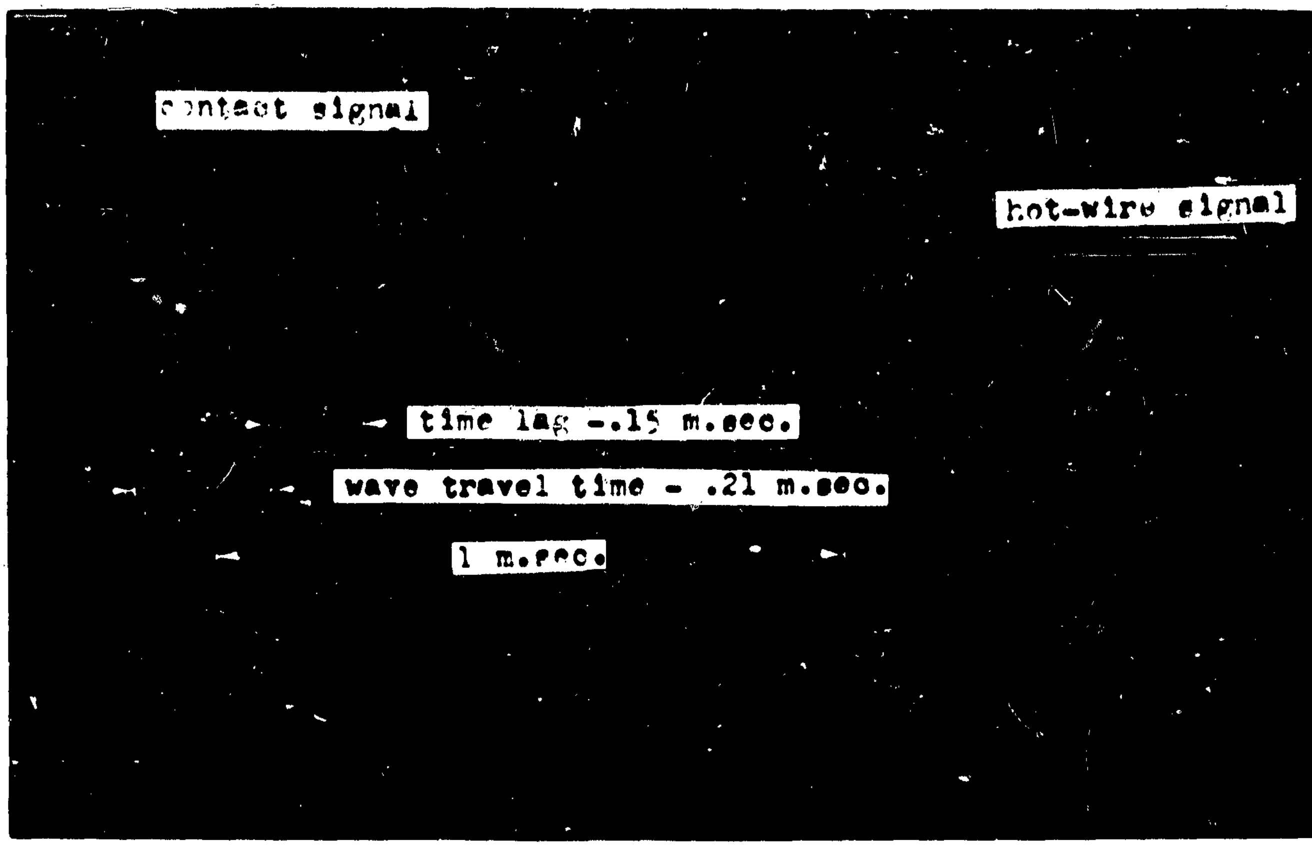


Figure 16. Still Water. Steel Case. Piston Impulse Test

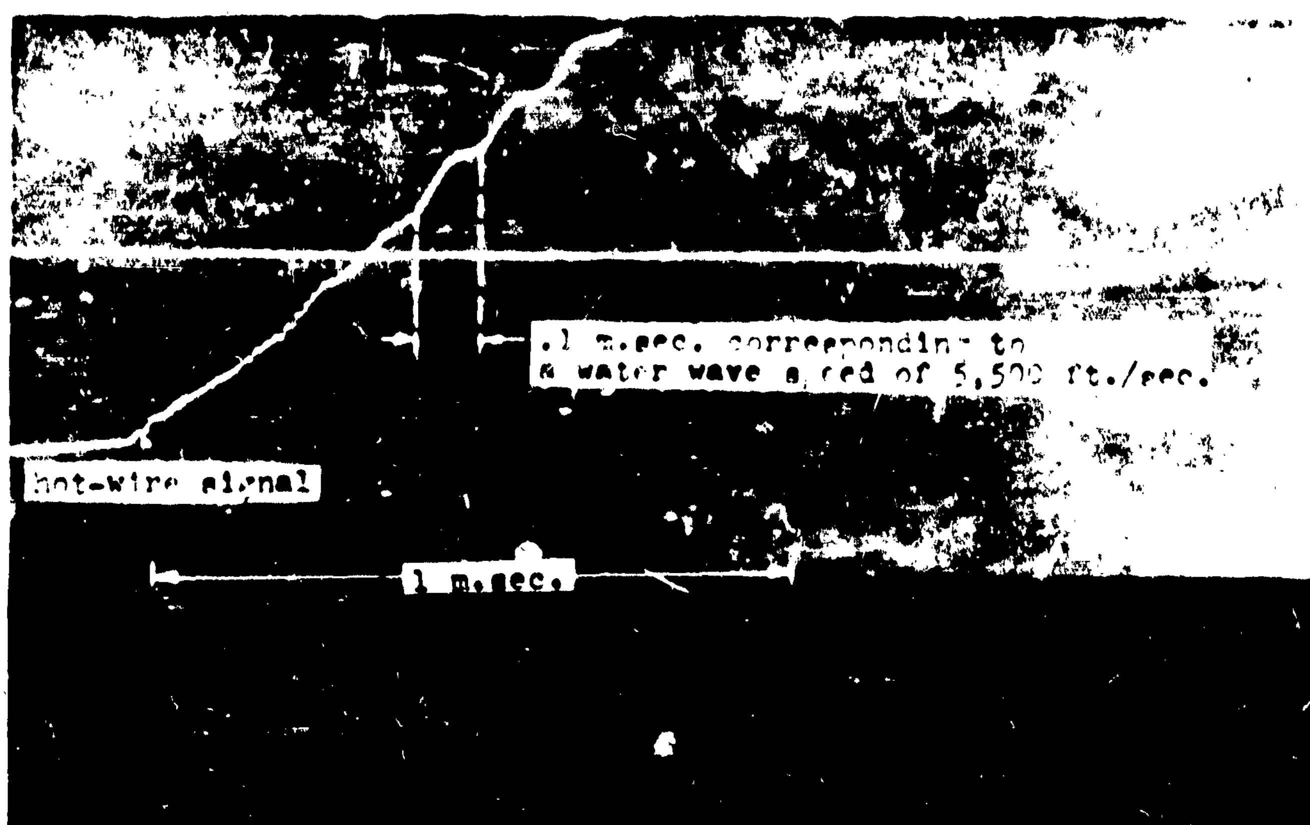


Figure 17. [illegible]

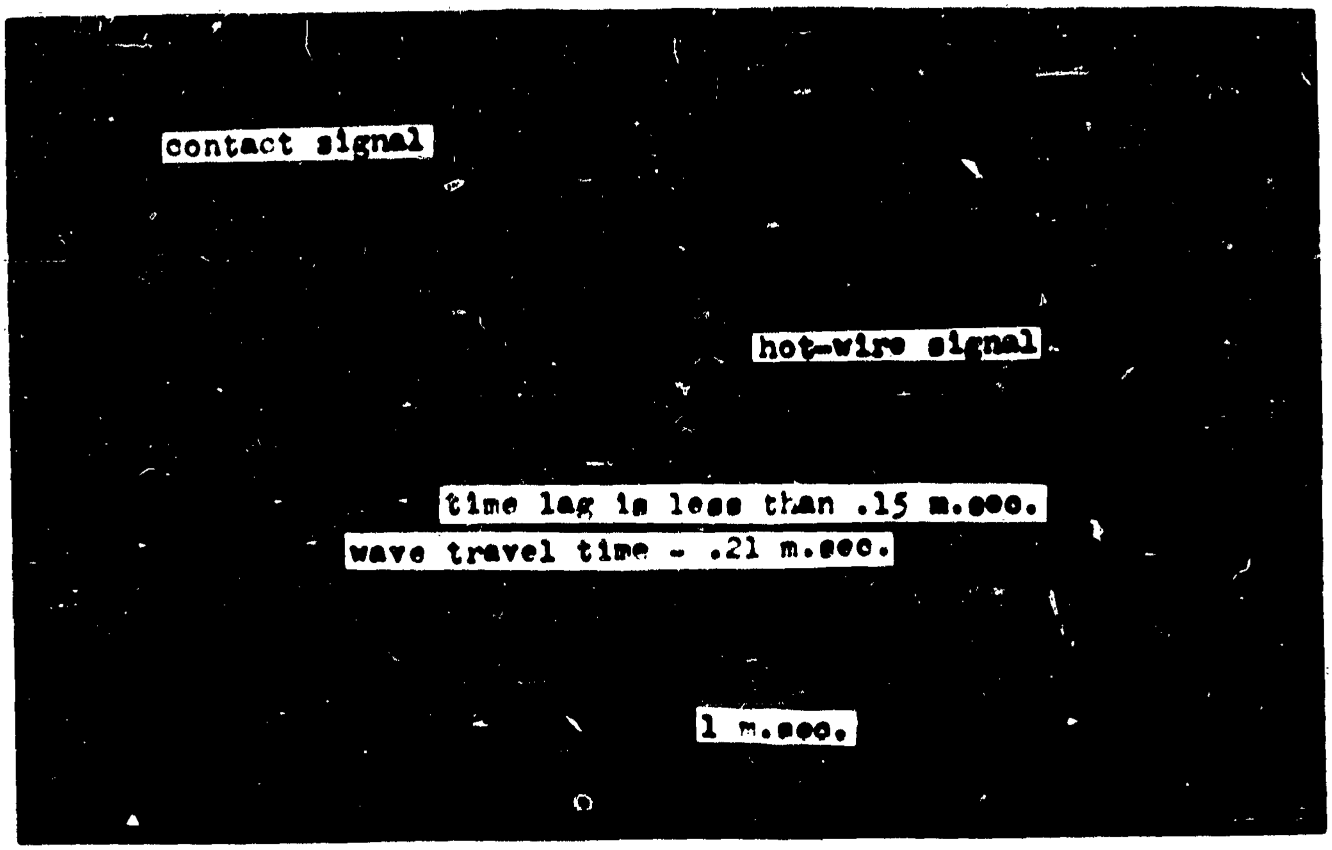


Figure 1?. Piston Impulse Test, Added Steady Flow With Steel

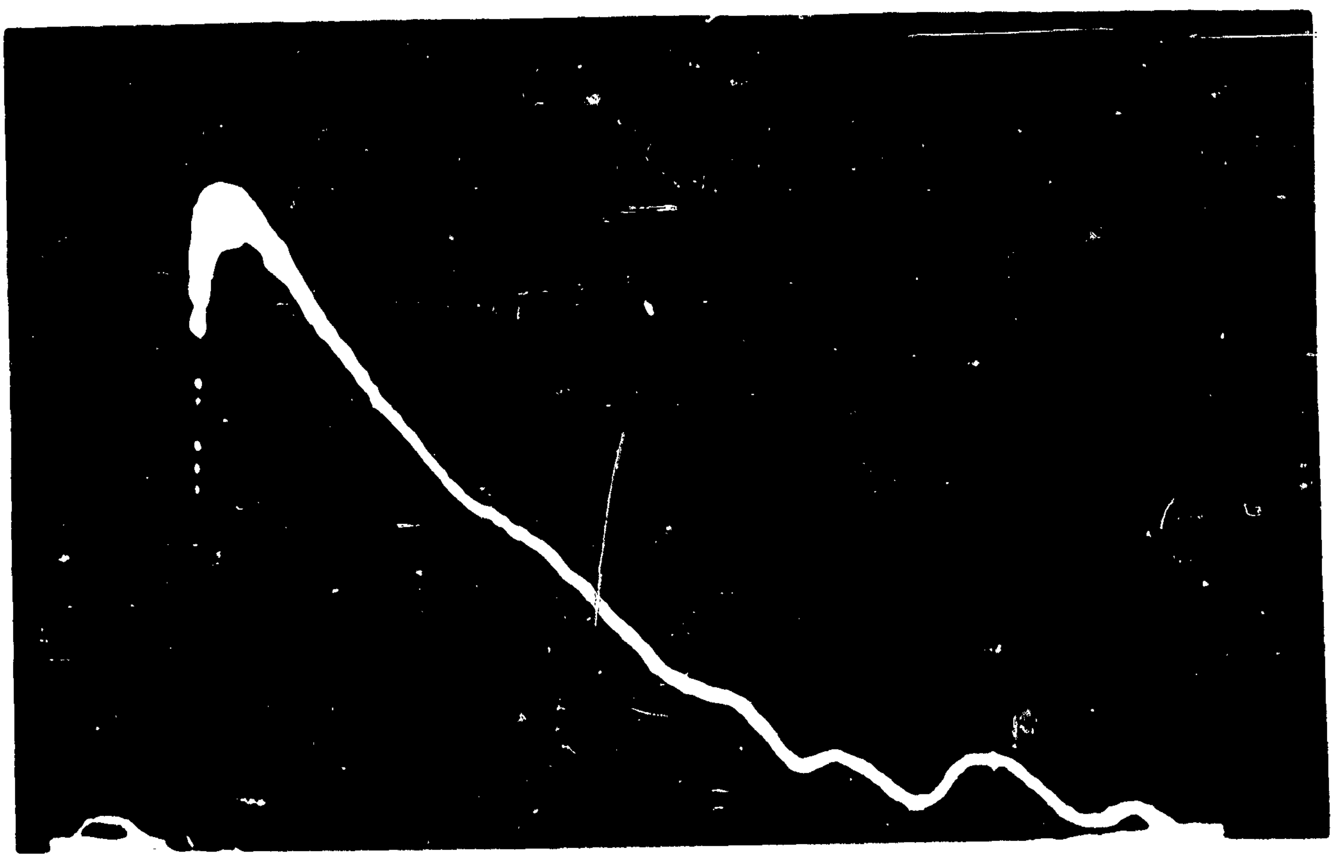


Figure [illegible] Ty[illegible] [illegible] Step F[illegible]

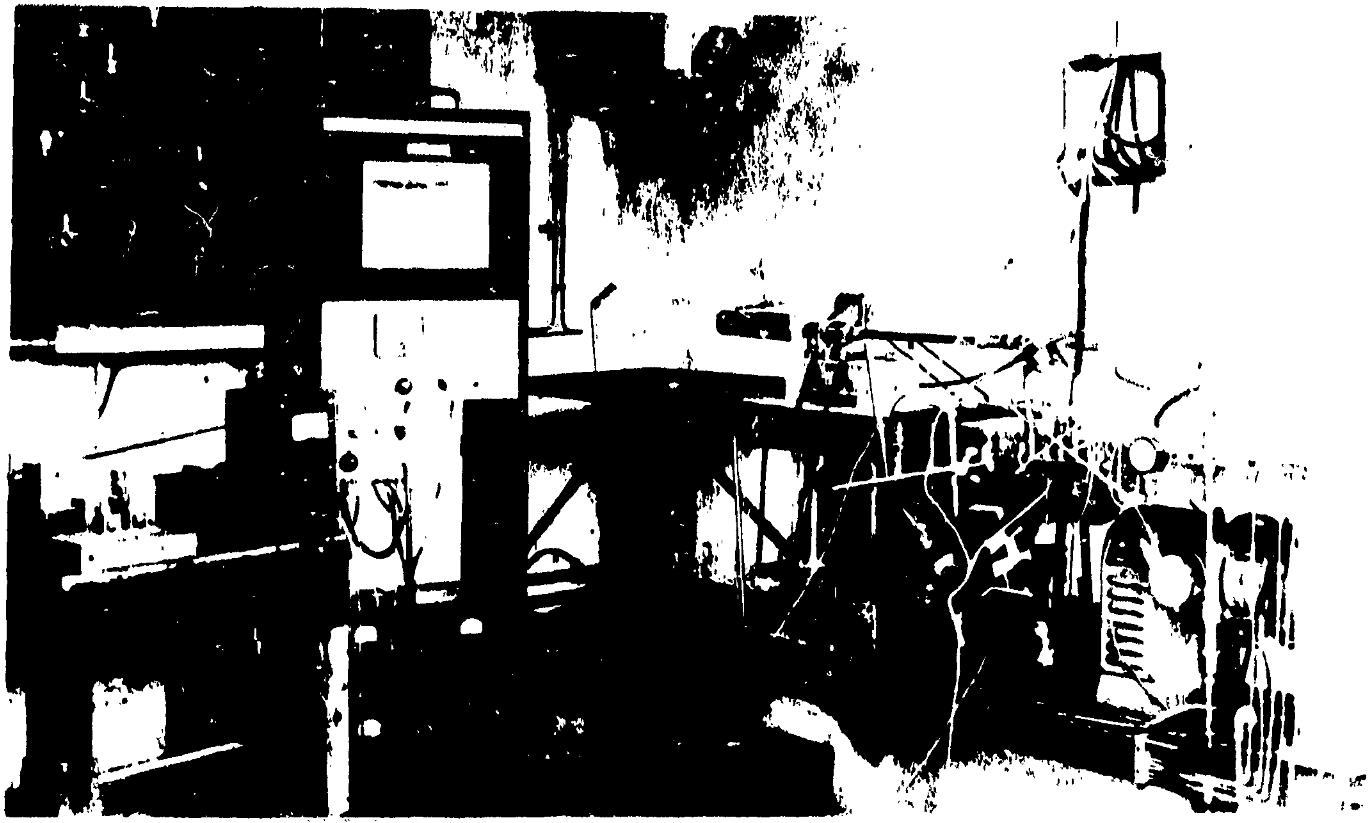


FIGURE 20a:
PULSING UNIT-PHOTOELECTRIC CELL ARRANGEMENT
(3rd SYSTEM)

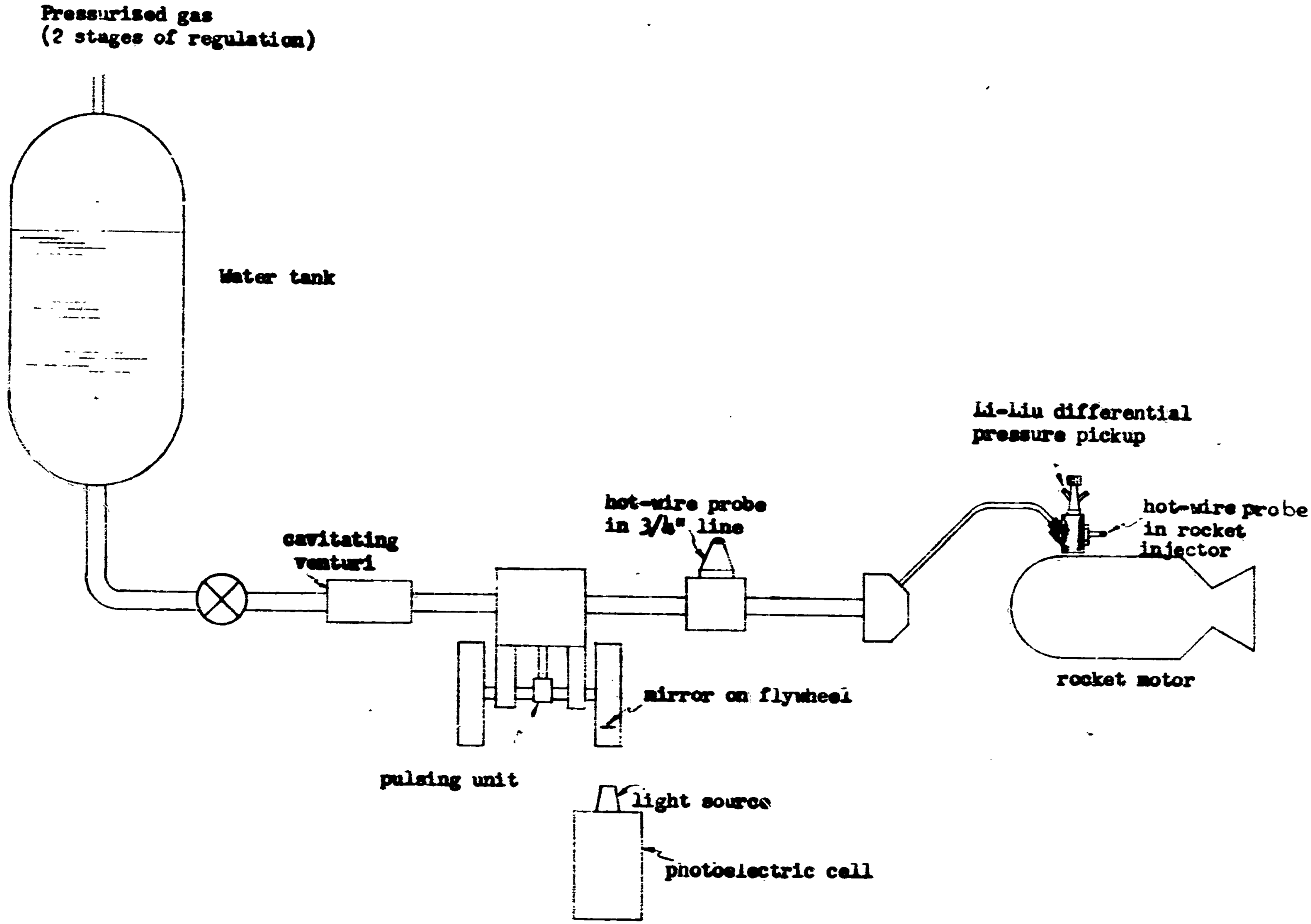


FIGURE 20b DIAGRAM OF 3rd SYSTEM

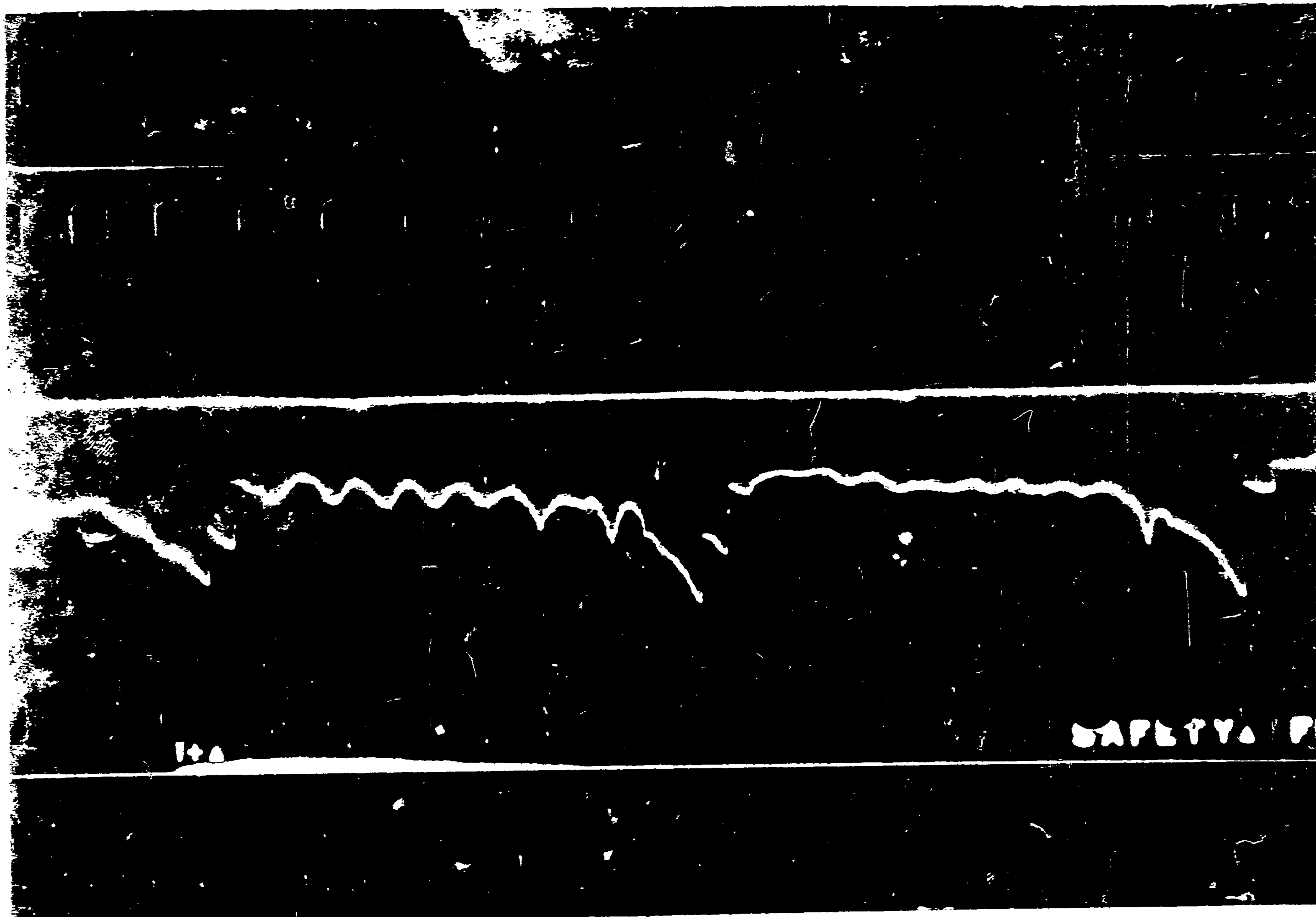


FIGURE 21:
TYPICAL RUN USING 1/4" LINE HOUSING

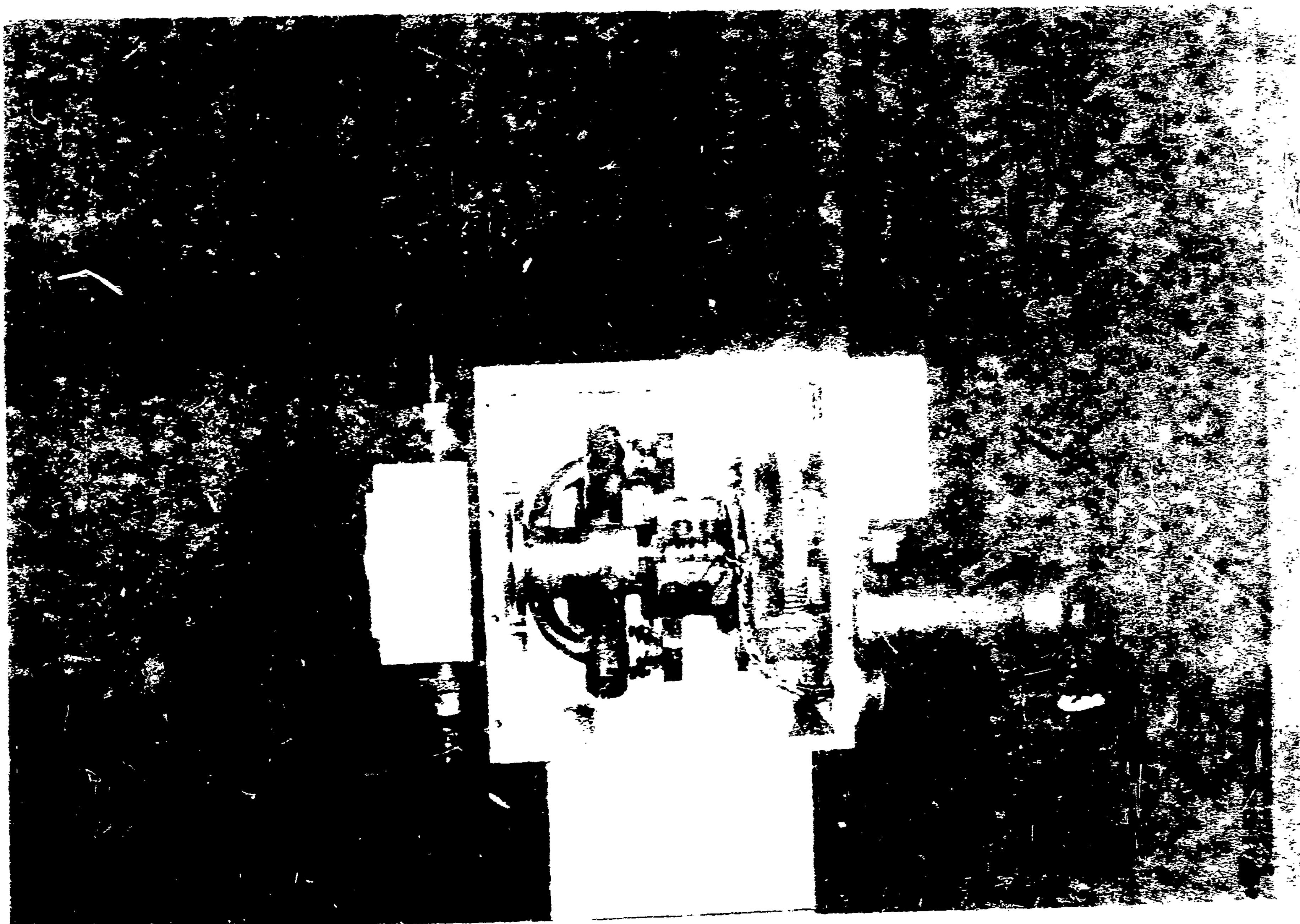


FIGURE 22
LI FLOWMETER-INTERIOR